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AEROSPACE INSTRUMENTATION
SYMPOSIUM (4th) PRESENTATION ON

THE MEASUREMENT AND ANALYSIS OF ROTOR BLADE AIRLOADS AND THE RESULTING DYNAMIC RESPONSE OF A LARGE TANDEM ROTOR HELICOPTER,

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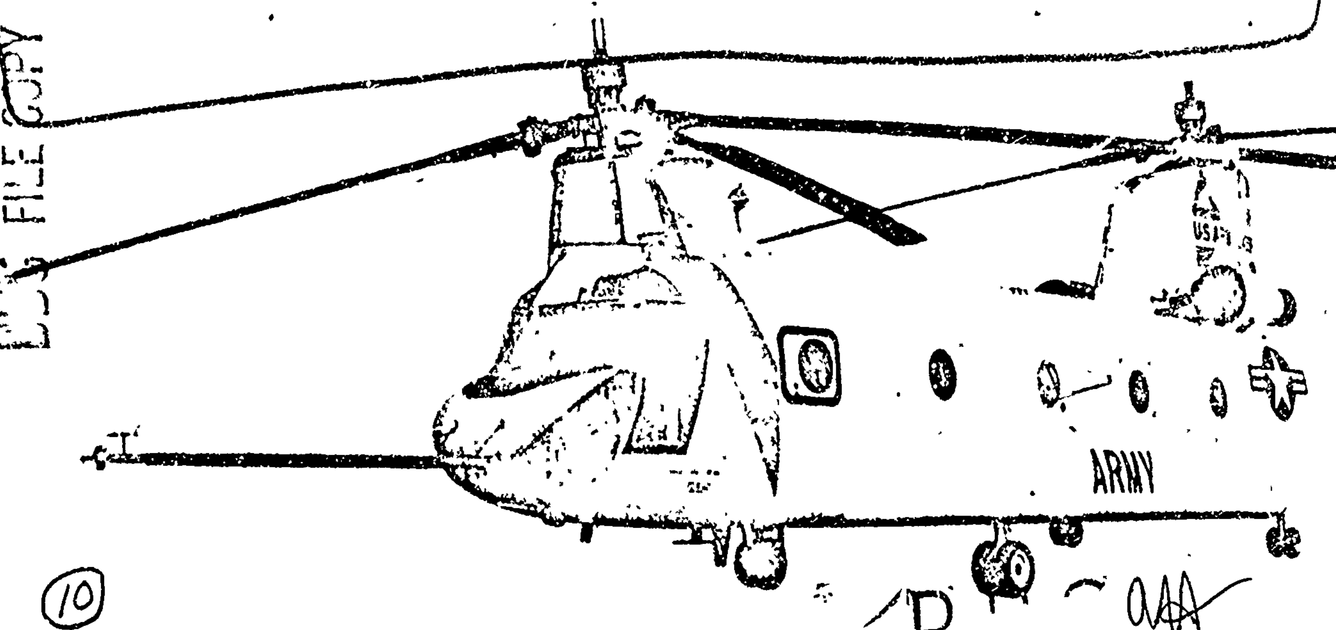

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ABSTRACT

A highly instrumented tandem rotored helicopter has been flight tested to obtain rotor airload pressures, rotor blade bending, rotor hub motions, rotor shaft and control loads and the resulting fuselage vibration These data were recorded in flight on magnetic tape and ground processed using an analog to digital converter and extensive computer analyses. The systems and procedures utilized included extensive interaction calibration corrections. Analyses to determine the accuracy of the data have been developed to compare redundant but independent measurements. The results were prepared for review, analys s and further consideration with the aid of automatic plotting equipment.

ACKNOWLEDGMENTS

The sponsorship by the U. S. Army Aviation Material Laboratory for the New Tandem Rotor Airloads Program (Contract DA 44-177-AMC-124 (T)) provided the incentive and the largest portion of the support which made this program possible. The aid, suggestions, and discriminating judgements of Mr. John Yeates and his assistant, Mr. William T. Alexander, Jr., of the USA AML staff have had considerable beneficial influence on this program. The Vertol Division personnel who have provided unusually able support include Messrs. W. Grant, W. Koroljow, E. Haren of the Project Staff, Mr. E. Kunz and his Flight Test Instrumentation Staff and Mr. D. Touring and his Computer Programming Staff.

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SUMMARY

An extensively instrumented tandem rotor helicopter has been flight tested to obtain rotor blade airloads and the resulting rotor blade motions and bending moments, rotor shaft loads and moments and fuselage vibration. A unique aspect of the instrumentation was the use of rotor-hub-mounted amplifiers which reduced the quantity of sliprings required and minimized the effects of slipring noise. A magnetic tape system was used in flight to record the 237 data channels with sequencing used to provide alternate cycles of forward or aft rotor data. The resulting frequency-modulated analog flight signals were converted to digital form at the ground station with a sampling rate adequate for determination up to the tenth rotor harmonic. The calibration coefficients were applied by means of an IBM 7044 computer programmed to correct for all significant interactions in a first and second order calibration matrix. Rotor blade, rotor shaft, and other oscillating data were harmonically analyzed and phase corrected for recording and reproduction time shifts. With this correction, the voluminous data output was ready for analysis.

Data systems computer programs prepared to process the data were devised with emphasis on data checking and comparison. This emphasis was believed to be necessary since many hidden errors are possible with a system of this magnitude and degree of automation. Helicopter instrumentation characteristically is loaded by large steady or low frequency data which can cause sizeable variation in the higher harmonic data of particular interest. Therefore, polarity and nominal values of all data and harmonics of data were checked prior to any analysis.

A second approach used to generate confidence in the data was to provide redundancy in the measurements of the blade, shaft and fuselage data and by taking advantage of the static and dynamic equilibrium of these systems. For example, blade airloads measured by the pressure transducers are compared with blade loadings deduced from blade bending measurements Second, rotor loads are summed at the rotor shaft and compared with shaft bending and motion data. The third data comparison points are the shaft to fuselage joints with a comparison made between the fuselage accelerometer vibration data and the shaft reactions. The helicopter was also treated as a unit to show trim and acceleration equilibrium with the measured rotor forces. Thus all data are compared in series with the small unexplained differences giving an indication of the accuracy of the measurements.

INTRODUCTION

The determination of rotor aerodynamics with adequate accuracy to predict dynamic loads which has required decades of development still remains somewhat inadequate. Present analyses such as References 1, 2, and 3 follow an iterative computer oriented approach and require significant amounts of computer time. Generally, a low confidence level is generated by these analytical developments since good predictions are only obtained for those flight conditions which cause minor difficulties. Low speed transition flight and high forward speed with significant rotor loading conditions are not predicted by analysis with adequate certainty. Measurement of rotor airloads have been similarly limited by developmental problems, some mechanical, some electrical and other analytical. Measurements of rotor airloads of significant value were first obtained by Meyer and Falabella, Reference 4. This early work led to the NASA blade airloads model testing of References 5 and 6. Rotor airloads instrumentation capability has been extended to full scale flight testing with two-blade teetering-rotor tests of Reference 7, and the three-blade fully articulated tests of Reference 8. The latest known measurements of this sort are the three-blade, fully-articulated, tandem-rotor tests to be discussed. The helicopter used for these tests is shown in Figure 1. It is noted that this paper is limited to instrumentation and data processing aspects of this program with emphasis on philosophy. Further analysis of the rotor aerodynamics findings are to be available in Reference 9. The project will be summarized in Reference 10.

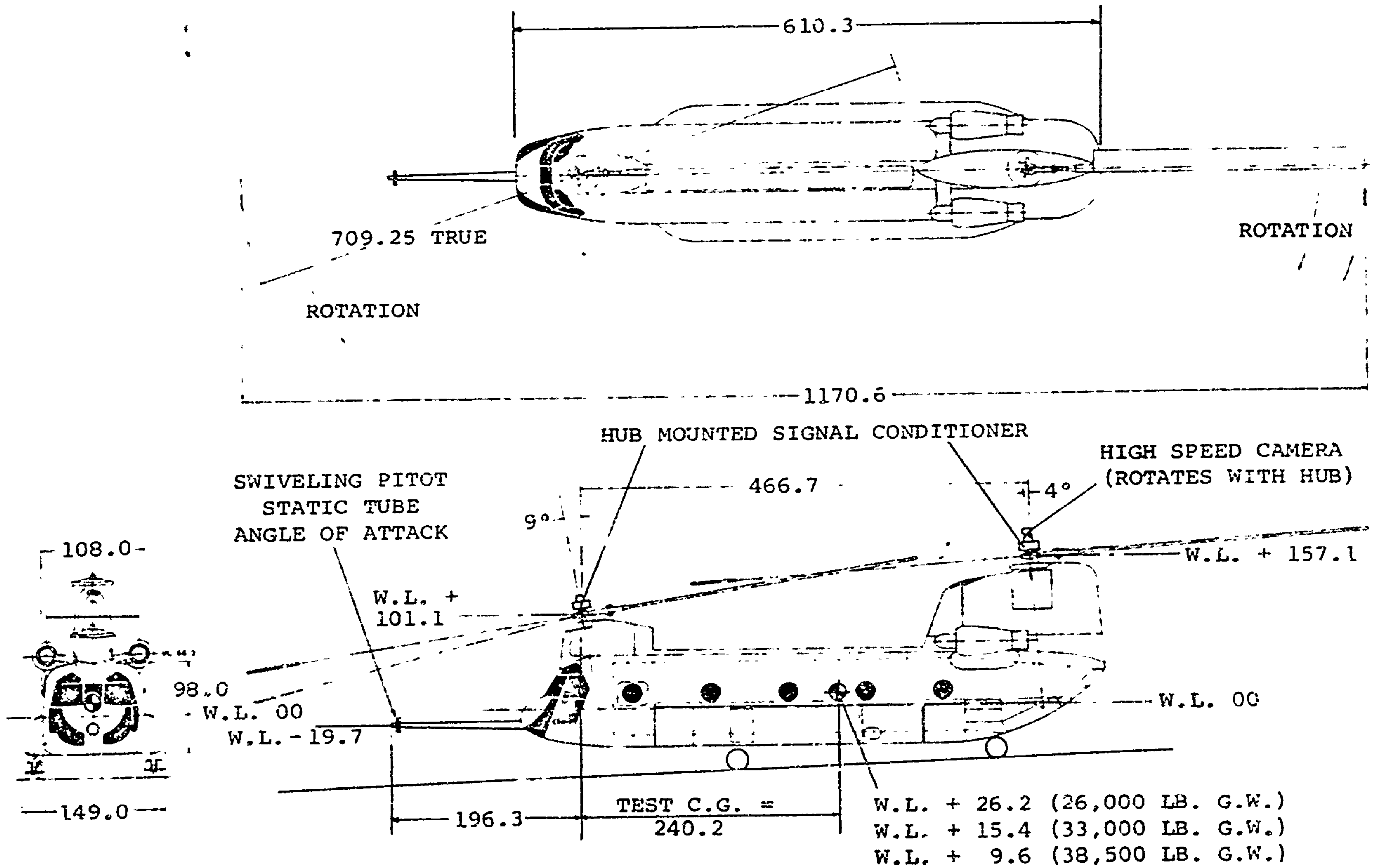

FIGURE 1. GENERAL ARRANGEMENT OF CH-47A HELICOPTER AS TESTED

TEST PROGRAM FORMULATION

In concept this program started as the marriage of a helicopter vibration reduction program and a further step in the U.S. Army's rotor airloads research. As a result of this heritage the instrumentation was unusually comprehensive with numerous measurements taken along the rotor loads path. Also, the overwhelming magnitude of the data expected from this program made it mandatory that the Vertol Division obtain and develop an automatic data digitizing capability. With this powerful data acquisition system it was desired to explore briefly the bounds of the flight envelope of the CH-47A helicopter. The most desirable data were measurements of the aerodynamic forces and moments on the rotor blades which can cause objectionable or limiting vibratory loads. The instrumentation provided on the blades (one blade on the forward and one on the aft rotor) is illustrated in Figure 2 and will be discussed in the following section of this report.

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The fundamental problem of this program has been where and how to apply effort and automation to evaluate and digest the resulting data. While there was little question that the data to be acquired was of considerable value, the magnitude of the data was of such proportion that manual sorting, evaluating and analysis was obviously impossible. The prior efforts on inflight measurement of rotor airloads, References 8 and 9, have produced large volumes of unknown data for this same reason and every indication was that a similar result of about three times the magnitude would occur from the subject program. It was decided that even if severe measures were required this result would be avoided. The output of data was to be of known accuracy. Instrumentation was to have unusually complete calibrations. Numerous automated data evaluation, digestion and correlation programs would be produced. Every procedure utilized on this program was to be questioned, the resulting accuracy evaluated, and the procedure improved whenever possible.

PLANNED REDUNDANCY IN DYNAMIC SYSTEM INSTRUMENTATION

This test program provided many chances for random nonsystematic human errors during operation and also numerous systematic errors on startup which suggested the need for redundant instrumentation and automated data checking procedures. This situation was aggravated because the test program was relatively short so that little time was available to recognize and correct errors. The idea of providing duplication of the measurements appears at first to be a wasteful approach. However, if the duplicating measurement determines the same value in a different manner, confidence is generated in the data and in the connecting analysis. The concepts used in this program are illustrated in Figure 3.

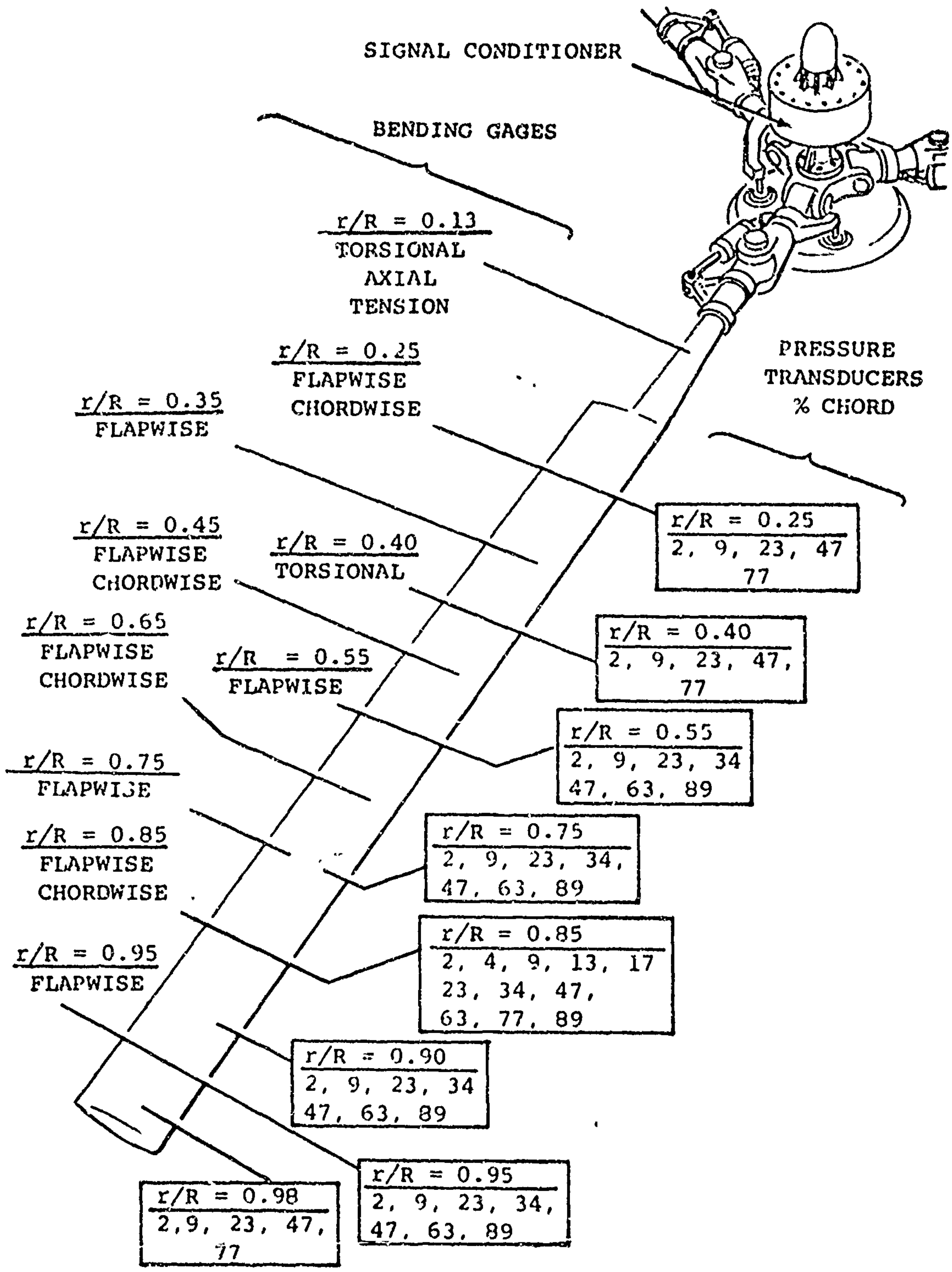


FIGURE 2. ILLUSTRATION OF ROTOR BLADE INSTRUMENTATION

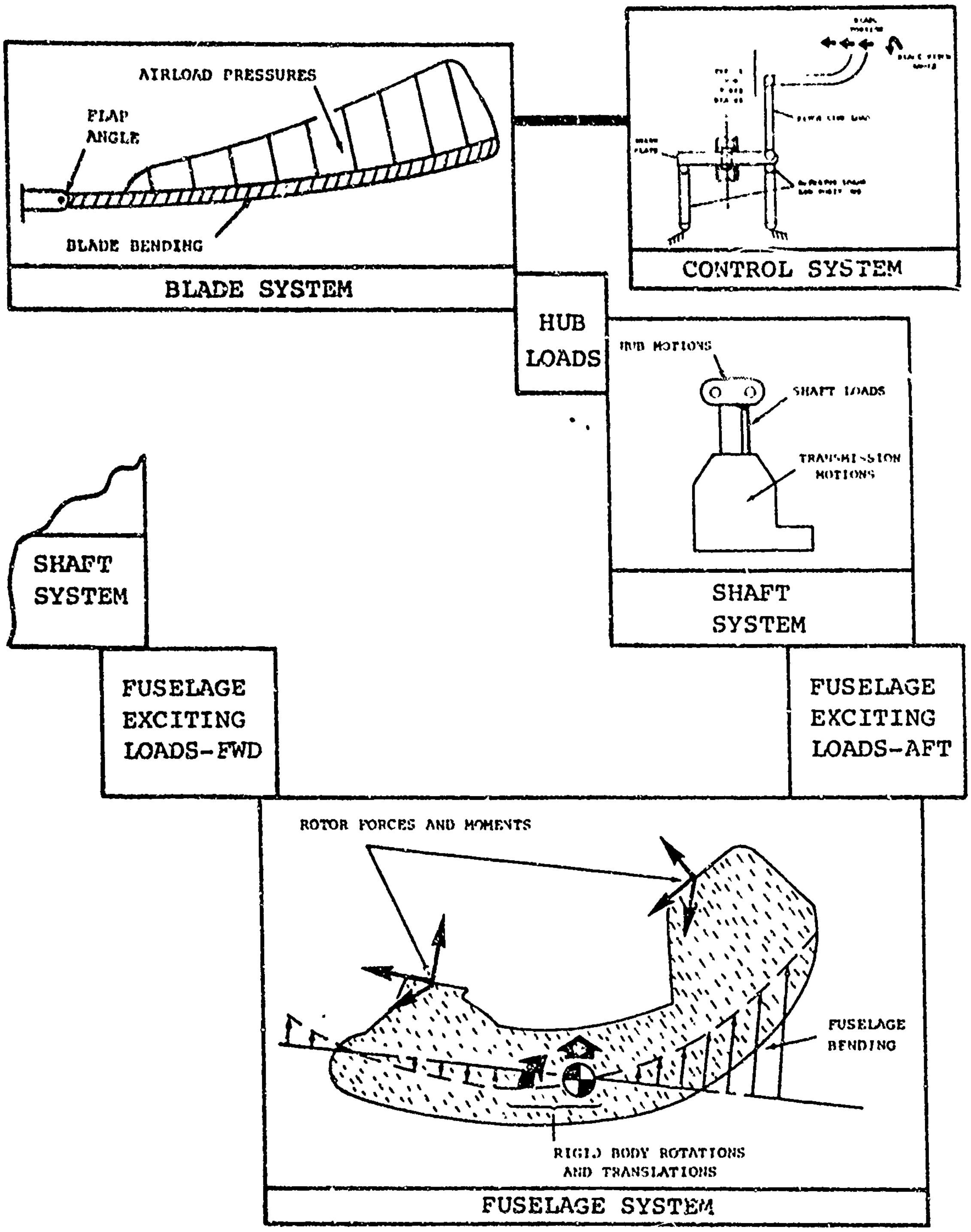


FIGURE 3. SCHEMATIC OF REDUNDANCE OF MEASUREMENTS

Principal interest has been directed to the blade system with the extensive pressure instrumentation illustrated in Figure 2, as the primary measurements. Supporting these measurements were blade bending strain gages and blade root angle transducers. Since the airloads bend the blades, measuring both bending and airloads was somewhat redundant, but there was interest in the magnitude of the contribution of blade elastic effect and in the blade structural response. An analysis of these data was prepared to determine, from the bending the airloads that were applied to the blades. Similarly, as shown in Figure 3, the blade and shaft systems are related through the rotor hub loads. The shaft system (illustrated in Figure 4) is also related to the fuselage system (illustrated in Figure 5) by means of the fuselage exciting forces and moments. In each of these systems, relating similar measurements gives more information than can be obtained from the separate measurements. At the system interfaces, equilibrium must prevail, therefore all data can be related and accuracy of the measurements established.

PRIORITIES AND MANDATORY INSTRUMENTATION

In a program of this magnitude and short duration of testing, it is unreasonable to ask for all instrumentation to be working all of the time. As a result of the redundancy provided, there were very few parameters which would seriously compromise the value of a flight. Therefore, a list of the few mandatory parameters and a required percentage of the remainding instrumentation was established. Limitations such as no two adjacent transducers could be inoperative were agreed upon. This approach gave the instrumentation people a realizable goal and provided for considerably better instrumentation availability than the minimum requirements. It was also found that this approach placed enough emphasis on the mandatory channels so that only a minimum of flights had to be aborted due to instrumentation.

In general the requirements were as follows:

Mandatory List (21 Parameters)

1. Flight Condition Indicators (airspeed, temperature, altitude, attitude gyro, attitude vanes)
2. Basic Rotor Data (flap, lag and pitch angles, azimuth position, blade tension, pitch link force)
3. System Operation Signals (sequencer position, voice recording, record coder)

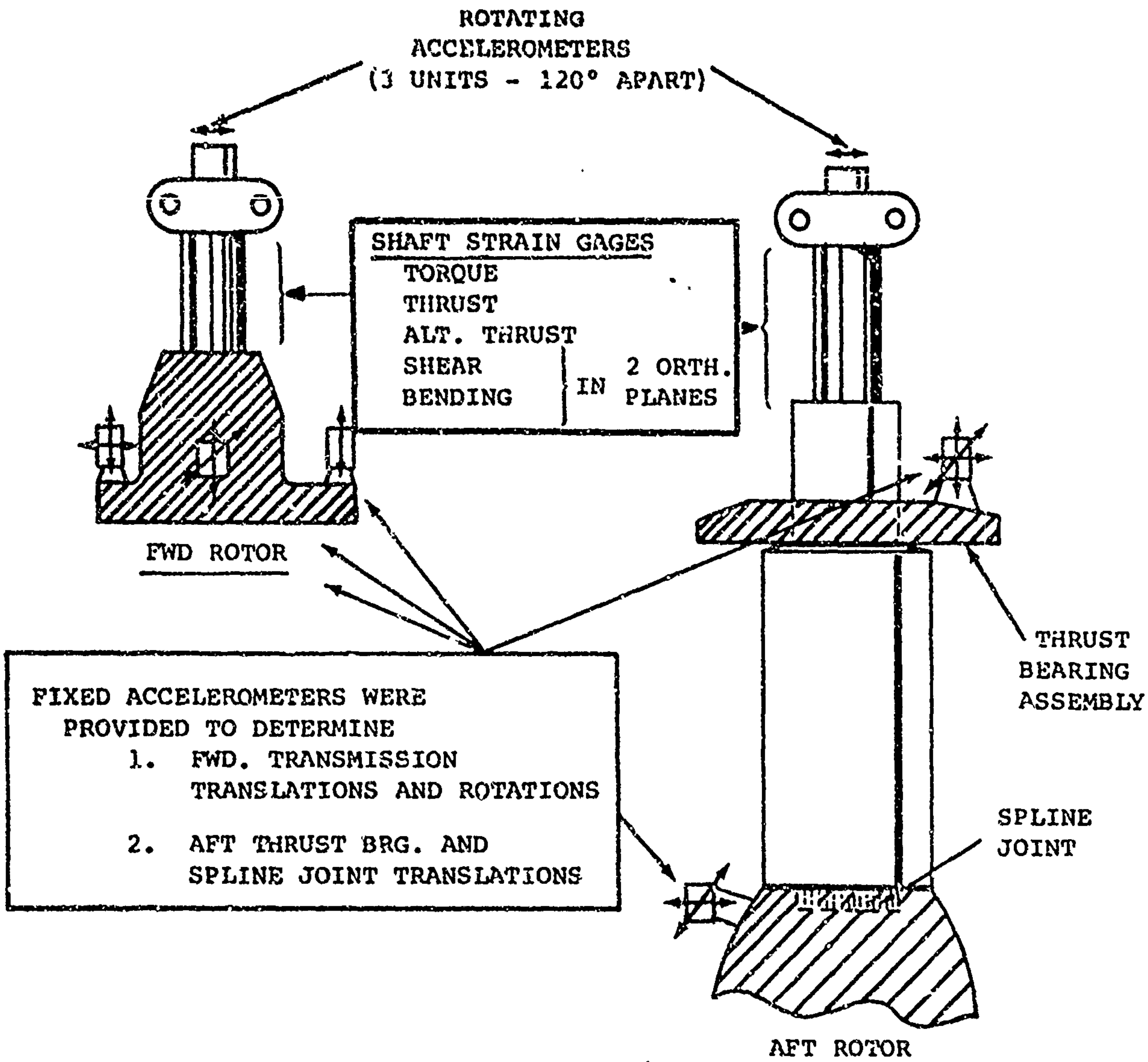


FIGURE 4. SCHEMATIC OF ROTOR LOADS AND HUB RESPONSE INSTRUMENTATION

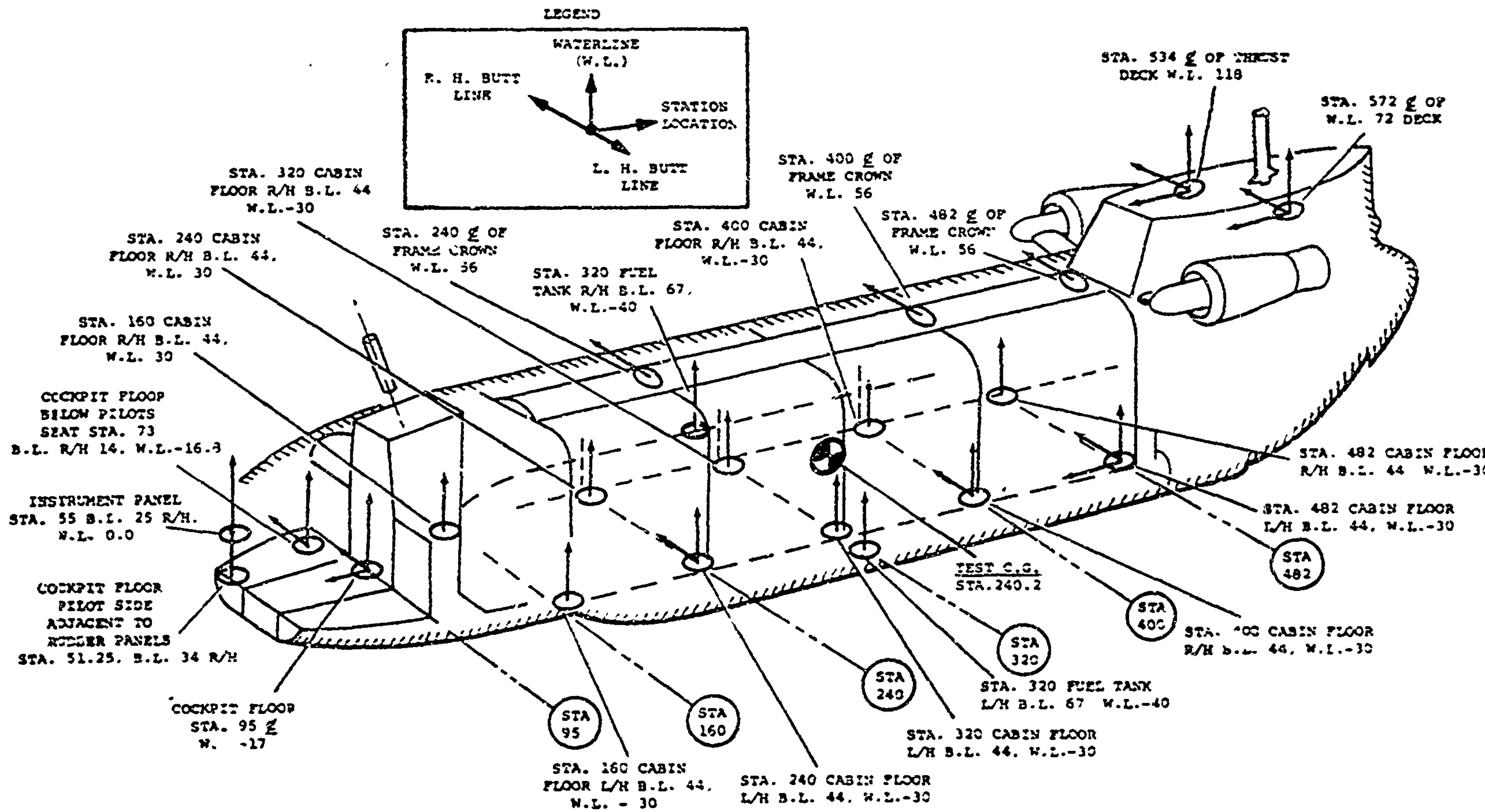


FIGURE 5. LOCATIONS AND ORIENTATION OF FUSELAGE RESPONSE ACCELEROMETERS

List of Transducers Required to Meet Minimum Availability Requirements

This list of transducers comprised the majority of the instrumentation with 204 parameters included. The criteria which had to be satisfied prior to a flight were the following:

1. No adjacent pressure transducers or blade bending strain gages could be inoperative.
2. At least one transducer of each type was required to be operative at each blade or fuselage station that was instrumented.
3. Rotor-shaft bending gages.
4. Instrumentation for rotor hub and transmission motions, and the swash-plate position instrumentation which augmented the mandatory blade pitch transducers, were highly desirable but of second priority; a flight could be initiated without these systems working, if necessary.

Not to Delay Flight List Requirements

These parameters were not of primary interest and generally provided duplicate data to support the mandatory instrumentation in the event of an inflight failure. Included were:

Engine Operation Data
Attitude Rates
Pilot Control Positions
Control System Loads

In cases of conflicts of criteria, pressure data always pre-empted blade bending data which always pre-empted shaft data which always pre-empted fuselage data.

SYSTEM REQUIREMENTS BEFORE TESTING

The successful operation of a highly automated system processing many parameters with a sample rate of ten thousand per second is an exacting task. With the pressure of schedules and budgets it is essential that each work item be accomplished thoroughly and accurately. By far the most troublesome problem is communication. The entire data acquisition system must be analyzed to answer questions which include the following:

1. What is to be measured and why?
2. What is the result that is expected?
3. How should the instruments be calibrated to measure the expected result?

4. What other varying parameters could obscure the expected result? Can the instruments be selected or designed to avoid interaction with these parameters?

5. Will the minimum significant signal, especially in the small amplitude higher harmonics, be large enough to discriminate from instrument background "noise"? Is interest in the signal or magnitude of the "noise" the limiting constraint?

6. During operation, what checks must be performed to ensure accuracy and repeatability? What are the reference zero's and standardizing calibrations?

7. In processing data, what form should the results take to simplify performing subsequent manipulations?

8. How are the data identified? Where can it be found? What safeguards have been taken to prevent mistakes in identity?

9. Can the results be processed, combined, or otherwise digested to improve understanding or comprehension?

10. How should the success of the project be measured?

In one form or another, these questions are either asked by or from all participants of such a project. Since far too many personnel are involved to permit personal answers, these questions must be analyzed, the results documented, and the documentation must be widely circulated for comments and criticism. Above all, the possibility of an answer to a problem being hidden away in someone's desk without proper documentation must be vigorously opposed to prevent erroneous results.

A good example of this general philosophy is shown in the solution used for the problem of establishing required accuracies. The usual approach is for the analytical staff to set requirements based on the significant figures of the problem with no regard to the difficulties the requirement may cause. The approach taken in this program was the requirement of a maximum practical accuracy of the equipment together with an analysis (and appropriate experimental verification) to document the measurement accuracy obtained. This analysis also included a review of the limiting factors with a discussion as to why better accuracy was not pursued at this time. The principal advantage of this approach is that resulting instrumentation design problems did not inadvertantly push the state of the art and the emphasis was shifted toward a review of present accomplishments and a general questioning of all assumptions. Also, the problem of selecting those signals which required increases in accuracy could be made intelligently since readily available accuracy and difficulty of improvement had been assessed.

Another obstacle to good data which had to be overcome prior to testing was that the personnel who operate the instrumentation felt that if the transducers and circuits would work, their job was finished. All personnel involved in such a project must feel responsible for the final data. Three guidelines were established in this program which were particularly beneficial. First, no test flights were initiated until the responsible instrumentation people were ready to give assurance that correctly measured data would be obtained. Second, any instrumentation that was questionable prior to flight and was not required to satisfy the preflight criteria was turned off. Flight was delayed until the criteria could be satisfied with assurance. Third, to qualify a measurement circuit for inflight recording, at least a one point calibration was required after the instrument was installed on the aircraft. The calibration load was required to be at least 10 percent of the maximum bench calibration value. These tests were not complete until the data were recorded on the inflight recording system, played back and digitized in the ground station and processed through the data system. Many systematic errors, caused mainly by poor communication, were isolated and eliminated prior to generation of questionable data by this approach. At the time, this process seemed to cause a sizeable delay to data acquisition; however, the confidence in the data generated more than compensated for this drawback. Believable, useable data were generated in a shorter period of time than had been the experience with other approaches to this problem.

THE INSTRUMENTATION SYSTEM

PHILOSOPHY

The instrumentation system was to provide data in a reliable manner within a substantiated maximum value of error and in a form which was usable for automated processing. Sensitivity changes, and drift corrections as functions of ambient temperature and interaction load value, were made during the computer processing. All instruments and systems were selected to meet accuracy targets and were laboratory evaluated in the temperature and vibration environment to prove their accuracy and integrity. The signals from most of the transducers were considered as dynamic measurements with all frequencies of information from zero to sixty cycles per second to be accurately determined. All signals were corrected for phase shifts caused by the record and reproduce systems.

SIGNAL SEQUENCING, MULTIPLEXING AND RECORDING

The requirements for the inflight recording of approximately tw hundred thirty-seven signals on one fourteen track magnetic tape recorder made multiplexing necessary. The standard Inter Range Instrumentation Group (IRIG) narrow band frequency modulation (NBFM) method was used. Low level signals (zero to twenty millivolt) were conditioned to the NBFM signal using millivolt controlled oscillators (MVCO); similarly high level signals (zero to five volts) were conditioned using voltage controlled oscillators (VCO). These units were custom-built to a Boeing specification but did not differ appreciably from standard instruments.

It was also necessary to time share rotor data by alternately recording signals from one rotor for two rotor cycles then switching and recording the other rotor. Although a compromise, it satisfied the requirement for instantaneous recording since several adjacent rotor cycles of data were to be averaged during processing.

The inputs to the recording system VCO's were obtained from signal conditioning and standardizing units. As shown in Figure 6 separate systems for each of the two rotors and for the airframe instrumentation were provided with correlating voice recordings from the pilot. Inflight time reference was based on rotor cycles and azimuth. For convenience, time was prerecorded on a separate track as a common input for identifying the digitizing process runs in the Ground Station.

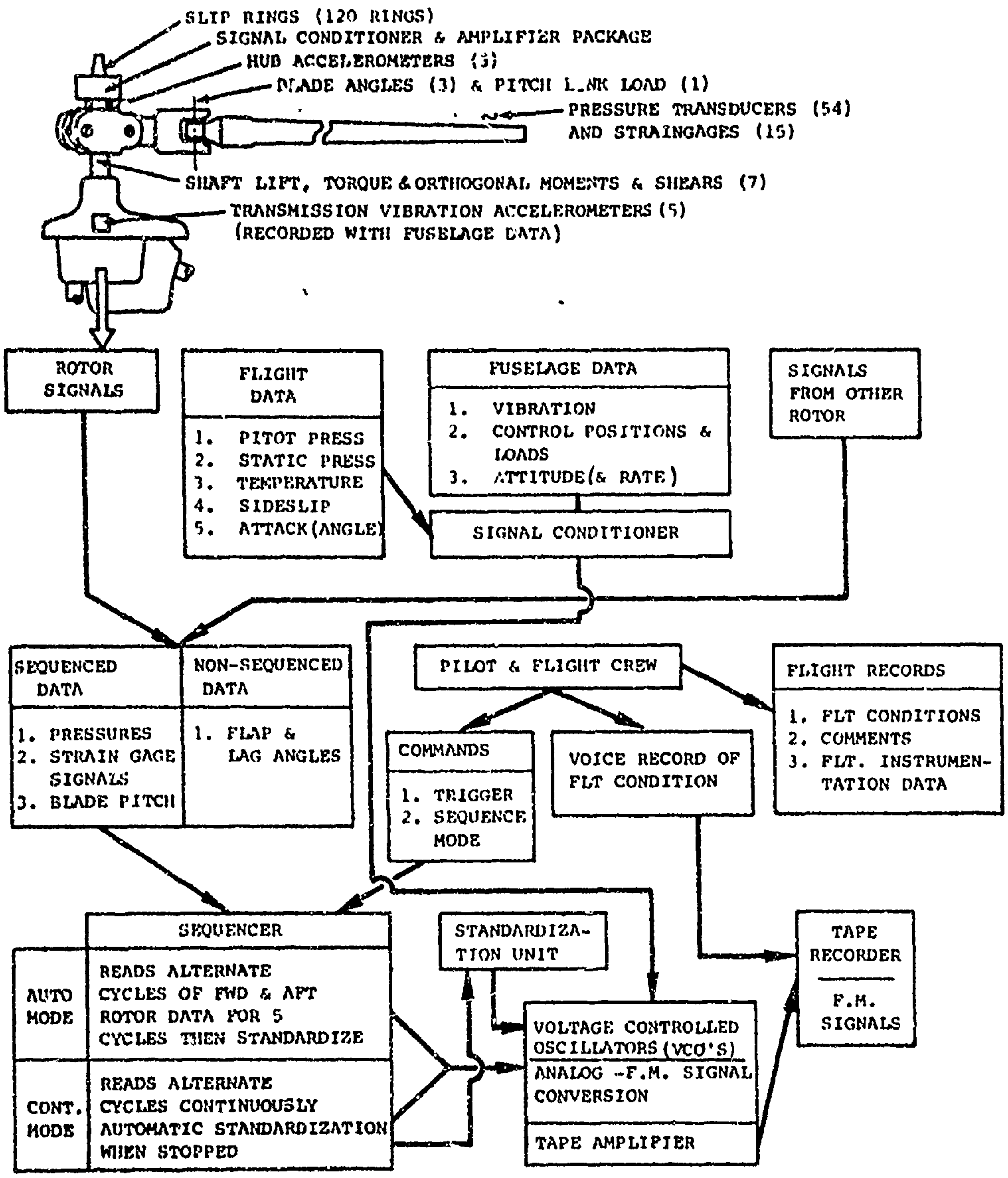


FIGURE 6. SCHEMATIC OF DATA ACQUISITION SYSTEM INSTALLED ON HELICOPTER

ROTOR INSTRUMENTATION

The rotor instrumentation consisted of the blade instrumentation shown in Figure 2, blade root angle (flap, lag, and pitch), transducers and the rotor shaft and hub instrumentation shown in Figure 4. Two types of pressure transducers were considered for the blade differential pressure measurements. One was the NASA variable reluctance differential sensor which had been used in the programs documented in References 7 and 8. The other choice was the Battelle - Scientific Advances absolute and differential flush diaphram strain gage transducers. The Scientific Advances transducer was chosen because they were easier to install and replace, and with the use of pairs of absolute sensors on the top and bottom of the blade, it would not be necessary to drill the structural spar of the blade. The choice was not a clear-cut one because the Scientific Advances transducers required a signal conditioning system which necessitated a large development effort. Operational amplifiers, located on the rotating system, were needed to preamplify the lower level signals and to reduce the number of slip rings required.

End Instruments

Pressure transducers were used to measure the rotor airload (differential) pressure in a chordwise and spanwise array of blade locations as shown in Figure 2. The pressure transducers were installed as shown in Figure 7. The sensors were attached to the blades by bonding the tabs to the blade surface with an elastic adhesive which allowed negligible strain transmittal from the blade. A four-inch wide sleeve of an epoxy filler was applied around the chord of the blade at the sensor location. The effect was to have a flush diaphragm with little change of the airfoil dimensions. A plastic tube supported within the blade was used to port the differential transducers to the bottom blade surface. These units were the 5 to 20 psi absolute pressure transducers and three sensitivities (2, 5 and 10 psi) of the differential pressure units.

Strain Gages

Strain gages were installed on the rotor blades as shown in Figure 2 and the rotor shaft as noted in Figure 4. In all instances, epoxy backed foil gages were used except for the dynamic lift load gages on the rotor shafts. P type semi-conductor gages were used for this measurement because of the very small dynamic strain available.

Potentiometers

Potentiometers were used for indicating blade root angular positions in flap, lag, and pitch.

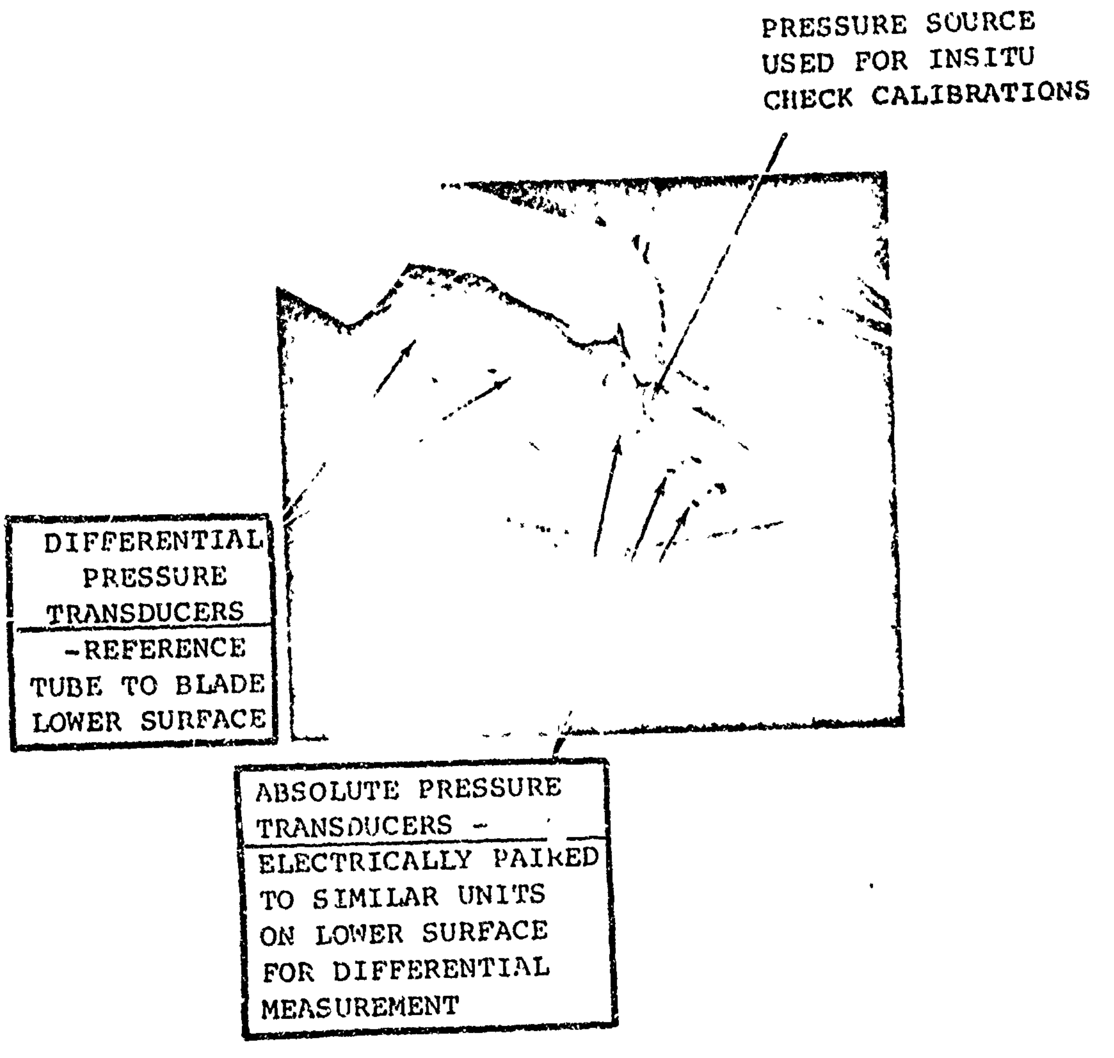


FIGURE 7. INSTALLATION OF PRESSURE TRANSDUCERS ON OUTBOARD END OF ROTOR BLADE

Signal Conditioning

The decision to use amplifiers in the rotating conditioner was based on three considerations. First, some of the differential measurements at the trailing edge were expected to have low outputs in range of three hundred micro-volts and it was felt that a preamplifier in the rotating system was necessary to keep a proper signal to noise ratio. Second, the available slip ring assemblies had insufficient capacity for the conventional four wire strain gage system, so a means of converting a differential signal to a single ended, signal was desired where a common signal return could be shared. Third, the amplifier afforded a good means of performing the algebraic addition of absolute pressure measurements to obtain differential signals prior to the slip rings. One of the circuit modules used for performing these functions is shown in Figure 8.

Further slip ring economy was required and was accomplished by the incorporation of ac to dc isolated power converters in the rotating system for pressure transducer excitation. These power circuits were comprised of a small transformer to provide isolation, a full wave rectifier, a 5 volt regulator diode, and a filter capacitor. Regulation was ensured by having a regulated power input, a regulator diode with a low temperature coefficient and a constant load. For the fifty-four pressure measurements on the instrumented blade, fifty-nine slip rings were needed. One ring was necessary for each amplifier output (plus one ring for a common signal return) and two rings for prime ac power to the strain gage power converters. Two additional rings were needed for supplying power to the operational amplifiers. To enhance reliability, the power supply employed several rings redundantly.

For the circuits where a pair of absolute transducers were used for differential measurements, a means of standardizing the sensitivity of one transducer to the other was necessary. This was accomplished by a series potentiometer in the excitation circuit of the more sensitive transducer. As explained later, the transducers were individually selected for each rotor blade location. The more sensitive ones were placed on the top of the blade. The shunt standardization resistors for the top and bottom transducers were then adjusted to the same equivalent pressure. The values of the shunt standardizing resistors were predetermined in laboratory calibrations of the transducers. The sensitivity normalization procedure had the following steps:

a. The bottom transducers were individually zero balanced by first removing the excitation of the top transducers and balancing the bottom unit to a null output. Power was then applied to both transducers and the top transducer was balanced to achieve a net null.

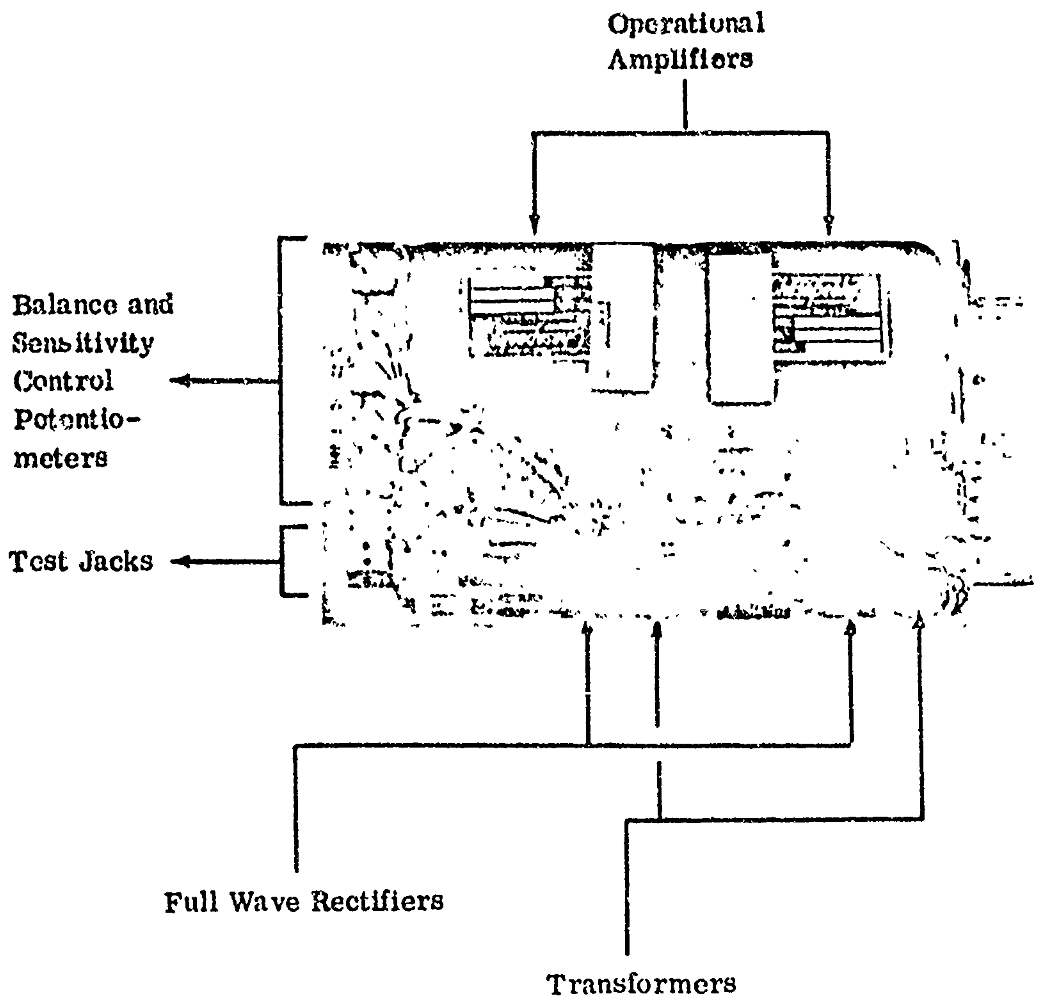


FIGURE 8. ROTOR HUB SIGNAL CONDITIONER MODULE FOR DIFFERENTIAL OUTPUT FROM TWO ABSOLUTE PRESSURE TRANSDUCERS

b. For sensitivity standardization, a shunt resistor was applied to one leg of the transducer of the pair which had the least sensitivity. A shunt of equal equivalent pressure was then applied to the other transducer. The series sensitivity control was adjusted until the net output of the pair was zero.

The balance procedure for the differential pairing of transducers was conventional and no sensitivity controls were necessary.

Since the transformers on the rotating power supplies were small and not designed for high isolation and because the operational amplifiers had only fair common mode rejection, the danger of undesirable common mode signals was present. To diminish this danger, several precautions were taken. First, a high impedance loop to aircraft ground was provided to keep the common mode currents as small as possible. The limiting factor in keeping the loop impedance high was the stray coupling due to the mechanical proximity of the wiring to the aircraft structure. The potential mid-points of the transducer circuits were connected to the output common to provide a balance path for common mode currents. With these precautions, the output of the amplifier still had an average peak-to-peak output of fifteen millivolts from the common mode signal (in addition to four millivolts peak-to-peak random noise generated internally in the amplifier). Because the information spectrum necessary for the airload study was only zero to sixty cycles per second, a low pass filter was employed to diminish the undesired common mode signal and noise to less than five-tenths millivolt peak-to-peak. The filter was followed by a T pad attenuator for signal level control and a constant impedance match to the filter. The MVCO followed the filter.

As mentioned previously, data from the forward and aft instrumented rotor blades were time shared by the recording system as an economy measure. Data from one rotor were recorded for two rotor cycles followed by the other rotor for two rotor cycles. The first rotor cycle was provided to allow the switching transients to decay and to provide for relay cycle time. Data were reduced from the second rotor cycle. The signal switching task was accomplished by a group of six pole double throw relays which switched the signal leads and the shield. Both rotors had identical transducer configurations and were switched on a one-for-one basis. This switching was done at the amplifier output (downstream of the slip ring) so that the filters, T pad attenuators, and the MVCO's were also time shared.

The inflight sensitivity and zero reference standardization corrections were also provided by the signal conditioning units. Short circuit and reference millivolt signals were substituted for the data signals at the MVO inputs to provide standardizing signals. An operational amplifier zero drift reference signal was also provided by removing the transducer excitation.

AIRFRAME INSTRUMENTATION

The airframe instrumentation consisted of flight attitude and flight condition transducers, various control system measurements and the accelerometers illustrated in Figures 4 and 5. This type of instrumentation is generally considered routine for helicopter flight testing except for the large number of transducers required. Since sequencing of the rotor signals and multiplexing of all signals provided ample recording capacity, the number of transducers also caused no problems. The more pertinent details of this system are the following:

End Instruments

Accelerometers - Accelerometers were used to measure the aircraft response to the dynamic airloads. The type used was the force-balance type which afford a large accurate dynamic range and a high level (ten volt per g) output.

Potentiometers - Potentiometers were used for control actuator and attitude vanes position measurements.

Pressure Transducers - Pressure transducers were used to provide an airspeed and altitude recording.

Attitude and Rate Gyros - Attitude and rate gyros were also included.

Rotor Azimuth Reference - Rotor azimuth reference was provided by a magnetic pickup which sensed the rotation of the forward rotor hub.

Signal Conditioning

Conventional signal conditioning methods were used as an interface between the end instruments with the recording system. As is the usual case, each strain gage circuit had a balance control, and excitation voltage control and a means of applying a shunt resistance standardization. The strain gage signals were low level but of sufficient level to drive the MVCO's. Control of excitation voltage control and application of a voltage reference were functions of the signal conditioner for the potentiometers. The force balance accelerometers had a potentiometer voltage divider at the output in order to provide a level control. The conditioned potentiometer and accelerometer signals were high level. The signal conditioning system also included an inflight standardizer unit which provided several functions. Similar to the rotor standardization

units in sequence, it disconnected the driving signals to all low level and high level subcarrier oscillators and substituted a short circuit and a voltage reference signal. The recorded information from this sequence was used to correct the data for oscillator zero and sensitivity changes.

DISCRIMINATING AND DIGITIZING

Following a flight, the recorded data were reproduced to analog form in the Flight Test Telemetry and Data Processing Center (Ground Station). The NBFM data were discriminated by commercial pulse averaging discriminators. Discriminators for IRIG bands nine through sixteen had sixty cycle per second low pass constant amplitude filters in the output. Discriminators for the lower bands were equipped with low pass filters of frequencies consistent with the IRIG schedule (modulation index greater than five). Three sets of twelve discriminators were available to enable three multiplexed composite signals to be simultaneously discriminated into a total of thirty-six analog signals. At the same time, functions such as time and the once per revolution rotor azimuth reference pulse were reproduced from their separate FM tape recording tracks. These signals were input to the digitizing equipment as illustrated in the Figure 9 schematic.

The analog data were converted to eleven bit digital words and recorded again on magnetic tape in a special format. This tape then became the data which was processed in the manner to be described later. The digitizing process was accomplished by a forty channel high level multiplexer gated to an eleven bit analog to digital converter. The analog signals were connected to the multiplex inputs through patch panels and the addressing of the multiplexer was controlled by the computer in a sequence defined in the computer program. The sampling rate was also controlled by the computer and was established to be such that each of the thirty-six analog channels was sampled at a rate at least five times greater than the highest frequency expected to be of interest in the reproduced signal.

ACCURACY OF DIGITIZED DATA

The approach taken in attaining high accuracy data was to determine each error cause, to eliminate it if possible, and if not, to provide a means of correcting for the more significant errors. For example, blade pressure transducers were calibrated to determine their non-linearity and hysteresis, and the coefficients of zero shift and sensitivity change with temperature. Tests performed for previous programs using these transducers indicated negligible response to acceleration in the range anticipated in the environment. Linearity characteristic and temperature coefficient were compiled for each of the differential transducers and used during the computer processing to make a correction for non-linearity and temperature effects.

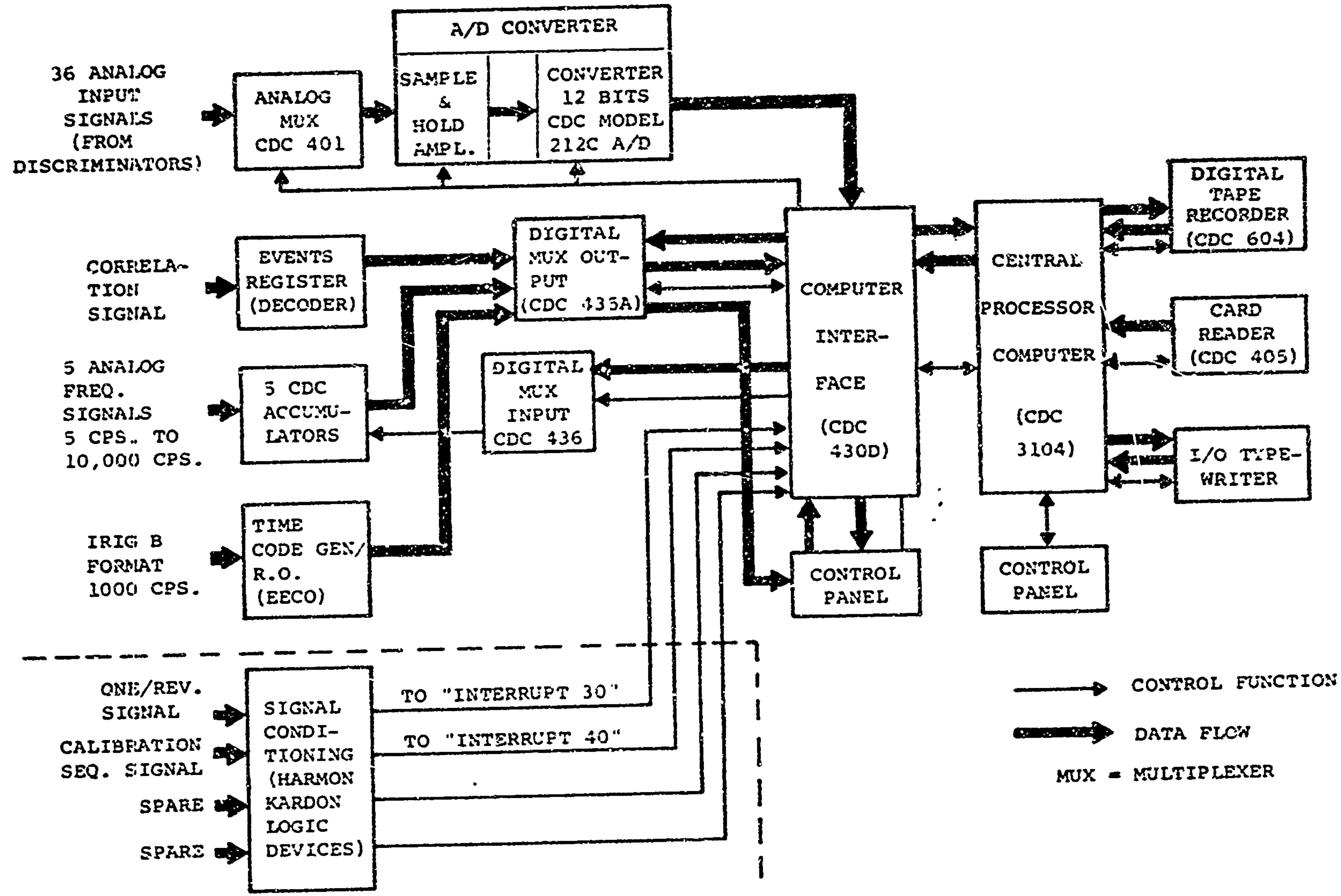


FIGURE 9. SCHEMATIC OF DIGITING EQUIPMENT IN GROUND STATION;

For differential pressure measurements where pairs of absolute transducers were used, non-linearity or temperature sensitivity corrections could not be made. To make these corrections, it would be necessary to know the instantaneous operating points for each absolute transducer because non-linearity is a function having a different value at each point of the transducer range and because sensitivity to temperature is also a function of the absolute pressure. The zero shift with temperature was corrected in the "back-to-back" absolute configuration by selecting pairs with good matches of the temperature sensitivity coefficient.

Another source of error which was compensated was lead wire resistance. A four wire system connected the blade pressure transducers to the rotating signal conditioners. The lead wire resistance was measured for each transducer and the shunt Real equivalent was corrected by the factor $\frac{4 R_L}{R_B}$ where R_L resistance per lead and R_B equaled bridge resistance (one hundred twenty ohms). An insitu pressure calibration was taken for each transducer to verify the Real equivalent.

To minimize inaccuracies due to the operational amplifiers, these units were required to meet the following specifications:

Temperature zero drift - four microvolts per ^{o}C referred to input.
Gain stability with temperature 0.1 percent per ^{o}C.
Gain stability with supply voltage - 0.5 percent per volt (power supplies used had one-tenth of one percent combined line and load regulation).

Every amplifier was tested to ensure compliance. The effect of zero drift was secondary because, as mentioned previously, a zero input signal reference was taken at the time of each data recording and used during the computing process to correct the data. Zero drift did compromise resolution because the data bandwidth had to be compressed so the combination of the transducer and amplifier zero drift plus the maximum data signal level would not exceed the recording system bandwidth. Approximately twenty-five percent of the bandwidth had to be sacrificed for drift of the system measuring the trailing edge differential pressures but only five percent was required for most of the other measurements on the blade. Following each data recording, a short circuit, and a voltage reference was substituted to the inputs of the MVCO's and the VCO's. This information was used during the computing process to correct the data for drift of the record/reproduce system.

Another potential source of error in the dynamic signals is the sensitivity attenuation and the phase shifts caused by the response of the transducers and the recording/reproduce system. To provide for these effects a nominal variation was established for use in data processing with a tolerance bandwidth for between transducer variations. For example, the accelerometers were required to have a flat amplitude characteristic within zero to plus ten percent

between zero and forty cycles per second, and to match a composite characteristic within one percent at twenty cycles and five percent at forty cycles per second. The phase characteristic with frequency similarly had to match within five degrees from a nominal characteristic compiled from the aggregate between zero and forty cycles per second. The dynamic characteristics of other parts of the recording systems were also determined. The blade pressure transducers had a calculated natural frequency of about 3,000 cycles per second so no corrections were required as to the phase shift in the transducer. Each operational amplifier was calibrated and an average phase characteristic determined. Phase calibrations were also performed on the record/reproduce system. These phase characteristics determined from calibration were used as a correction in data processing.

The accuracy of the data also depends on the calibrations. Considerable care was taken in calibrating the instrumented components with particular attention to interaction load effects discussed in the following section. It is believed that with the addition of the previously mentioned errors and the calibration errors, the maximum inaccuracy is less than ten percent in all cases and less than five percent for all primary data.

THE CALIBRATION PROGRAM

PHILOSOPHY

Most of the calibration requirements were based on instrumentation substantiation as previously discussed. It was decided, however, that the development of improved accuracy calibration procedures were required for this program. This was particularly true for the complexly shaped strain gaged structures such as the instrumented rotor blades and for the low strain sensitivity structures such as the rotor shafts. Through prior experience it was known that the load interaction coefficients of such instrumentation could be sizeable and that proper accounting for these coefficients was difficult. It was therefore decided to automate the calibration data acquisition and calibration data reduction. The guiding concepts utilized were the following:

1. Provide well defined requirements and establish common notation, reference axes and positive value direction.
2. Utilize automated calibration data acquisition whenever possible so that mistakes will be consistent and therefore correctable.
3. Apply all calibration forces from fixed points and use the computer to correct for deflections and to resolve the loads into a convenient structure reference.

The application of these principles to the rotor blades and shafts together with a summary of all calibration results are reviewed in the following discussion.

COMPUTER PROGRAMS FOR CALIBRATION

Rather than devote effort to laborious hand plotting of calibrations, all data were routinely input into one of three computer programs for analysis. Calibration quality was determined by calculating the maximum hysteresis and the maximum deviation from the best calibration relationship. Generally, it was assumed that the calibrations were not linear but that the coefficients, A, B_M and C_M, could take any one of the following forms to relate the measurement y to the various, M, readings, R_M.

$$Y_1 = A + \sum_{M=1}^{M=N} (B_M X_M + C_M X_M^2)$$

$$Y_2 = \sum_{M=1}^{M=N} (B_M X_M + C_M X_M^2)$$

$$Y_3 = A + \sum_{M=1}^{M=N} B_M X_M$$

$$Y_4 = A + \sum_{M=N}^{M=N} B_M X_M$$

$$Y_5 = BX$$

Where, of course, the last form is the one usually used for calibrations. The calibration analyses were devised to determine the best array of coefficients for minimum error over many types of loading and many values of the loads.

Routine Linear Least Squares Program

For the routine calibrations with single valued input and output data a simple least squares fit of a linear or a quadratic function was obtained depending on which function produced the least error. Similar curves were also fitted separately to the increasing calibration values and then to the decreasing values and the hysteresis was defined as the maximum distance between these two curves. Deviations of each of the data points from the best fit function were calculated and the maximum value of deviation was noted. Maximum hysteresis and deviation were also calculated as a percentage of the maximum value obtained during the calibration.

Combined Loads Calibrations

For combined loads calibrations the input and output are multivalued, the loads are applied from rather arbitrary fixed points and structural deflections generally are significant. This type of calibration would be practically impossible without an automated data reduction analysis. For what is believed to be a reasonably complete calibration of thirteen variations in the type of load application (or combinations thereof) and with about twenty-three load points taken for each type of load, the computer time (IBM 7044) required for the rotor blade analysis was approximately ten hours. The calculations for the relatively inelastic rotor shafts took about three hours.

The approach to the combined loads analysis is to first resolve the load geometry to a structure referenced loading. If the structure is a relatively inelastic cantilever (a rotor shaft), a simple deflection correction based on a measured beam tip deflection is used. For the elastic rotor blade structures, an iterative solution for the elastic deflections under the applied loads is performed using the calculated blade elastic characteristics. A comparison against measured structural deflections is made to check the calculations. Once the deflections and load system are resolved the calibration and interaction coefficients can be evaluated.

In evaluating the coefficients an exact solution for selected independent non-zero, calibration data points is first used to determine the most accurate form for the calibration relation. The number of data points used for this exact fit analysis depends on the relation which is assumed to apply. The relation with a constant and with first and second interaction coefficients, which are each functions of the six forces and moments, requires 13 data points per type of load. As expected, this analysis generally showed that the instrumented structures considered were linear and that there was no evidence of a constant term in

the calibration relation. The interaction coefficients were shown to be rather sizeable and various values of the coefficients were obtained depending on the combinations of loadings selected for the analysis. Therefore the next step was to perform a least squares fit on all the data points obtained to determine the best matrix of calibration coefficients. This task is not difficult for the 300 or so data points being considered since in the least squares fit the sums are first taken over the types of readings then over the number of points. This reduces the problem to a set of 36 linear equations in 36 unknowns which can be solved by conventional means.

ROTOR BLADE TESTS

The calibration of the rotor blades was performed in two steps. First, the axial tension gages were calibrated at high loads by whirl testing and then static calibrations of all gages under combined loads were performed. A discussion of this approach follows.

Whirl Tests

Whirl testing of the rotor blades was required to functionally test for structural integrity and to ensure that the blade balance will provide acceptably low aircraft vibration. This testing was also used to provide a high load calibration of the blade axial tension gages by utilizing centrifugal force. While this calibration is somewhat compromised in that all interaction on this gage must be assumed negligible, this procedure is necessary since provision of adequate attachment to cause the required 90,000 pounds load in the blade would be prohibitively expensive. The blade was static balanced prior to whirling so that the blade static moment, $\sigma(\beta)$, was accurately known. Therefore, the centrifugal force (CF) in the blade at the gage station could be accurately determined as:

$$CF = \Omega^2 [\sigma(\beta) - \sigma(\beta_R)]$$

where Ω - rotational speed
$\sigma(\beta_R)$ - estimated static mass moment of blade root fittings.

The resulting calibration data indicate linearity within one percent. The static calibration data, obtained at axial tension values up to 4,000 pounds to determine interactions, fully substantiated this calibration.

Combined Loads Calibration

When establishing the requirements for a combined loads calibration of an elastic structure, the boundary conditions must be such that the structural deflections can be calculated. Also, all loads must be applied from well-defined points fixed on the calibration fixture to well defined locations on the

structure being calibrated. For the rotor blade calibration the decision was made to use the standard blade root end hardware to restrain the inboard end of the blade. Restraint of the outboard end of the blade was provided by a strap and ballast weight arrangement. Photographs of these support fittings and the various load application devices are reproduced in Figure 10. Note that the root end hardware provides two orthogonal hinges and a blade pitch adjustment. As can be seen in the figure, the tip support consisted of steel straps attached through a ball joint to the blade tip by means of a fitting attached to the blade tip balance weight studs. Support straps were mounted to the overhead structure of the fixture and separate straps connected to a 4000 pound ballast weight. The ballast served to prevent excessive chordwise blade motions. Steel clamps fitted to the blade cross section were used to transmit the applied loads to the blade spar. Note that ball joints or equivalent means were used at each fitting to minimize friction.

The blade bending gages noted in Figure 2 were calibrated using a combined loading technique that featured simultaneous application of flapwise, chordwise, torsional and radial tension loads. Since flight loads are always combined loads, this method of calibration, with proper data analysis, provided for a more accurate and complete measure of the flight loads. Individual calibration loads were also applied to calibrate the strain gages up to the expected inflight loads. Due to blade stress considerations, this was not possible in the combined loads arrangement for some strain gage locations. Individual loads thus provided some definition of the upper end of the strain gage calibration curves. Also, the data obtained from the individual loads provided a measure of the accuracy gained in the determination of strain gage calibration factors by the combined load method.

As noted previously, the calibration data analysis included a check of the correctness of the load application techniques and elastic analysis through the use of measured blade deflections. For this purpose, steel scales with graduations of one hundredths of an inch were attached to the loading clamps. Surveyors transists (lens power of 18X) were used to record the deflection of the blade at the point of application of the primary calibration load.

The data acquisition system employed in the blade calibration was capable of automatically conditioning and recording the fifteen channels of strain gage data. The data were amplified, filtered and scanned by a high speed direct readout digital voltmeter. The voltmeter had a binary output which was fed into a converter which converted the data to decimal equivalents and stored it until the program control commanded the summary punch (IBM 526) to record the data on punched cards.

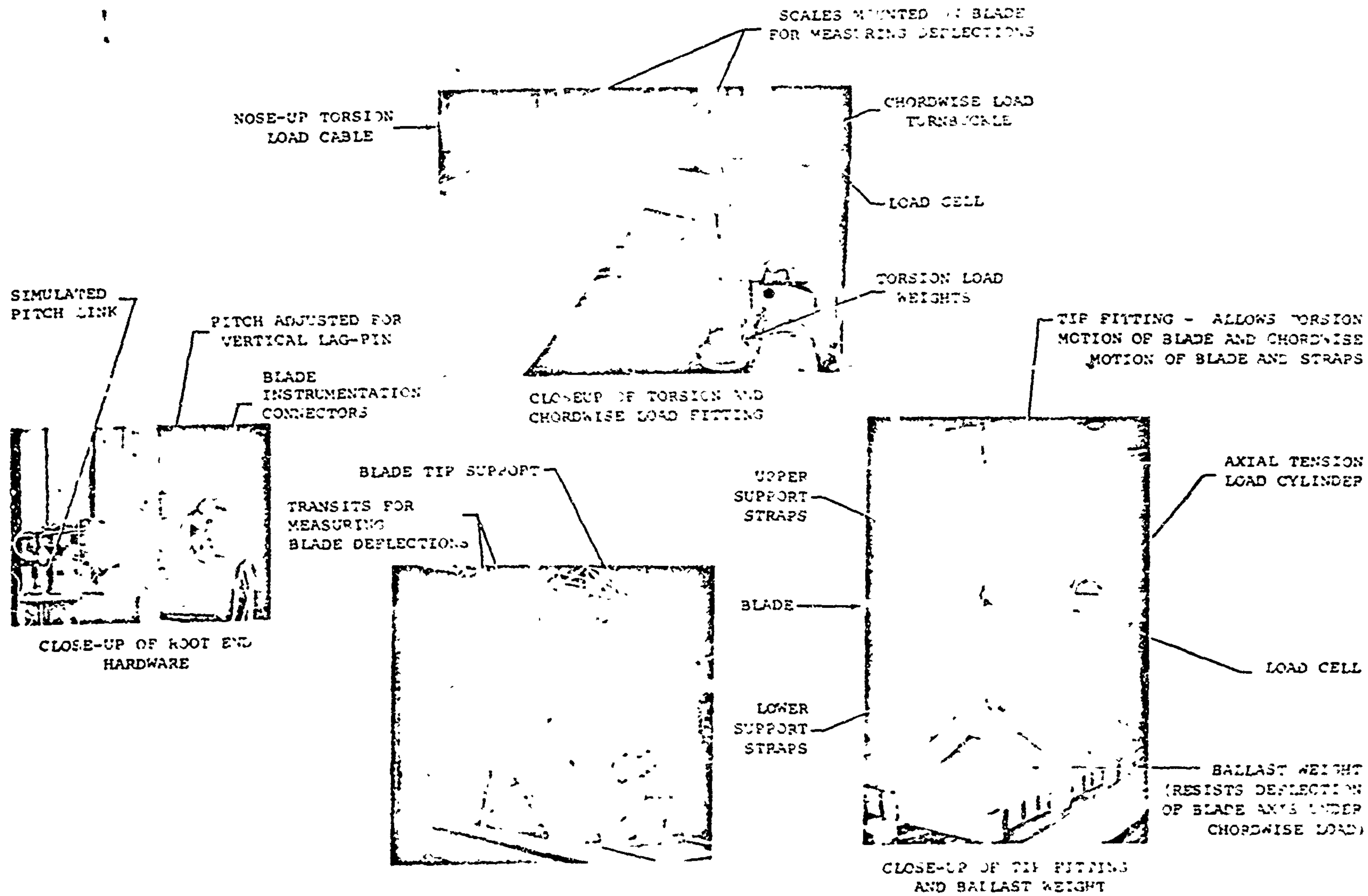


FIGURE 10. TEST FIXTURE FOR CALIBRATION OF ROTOR BLADES UNDER COMBINED LOAD

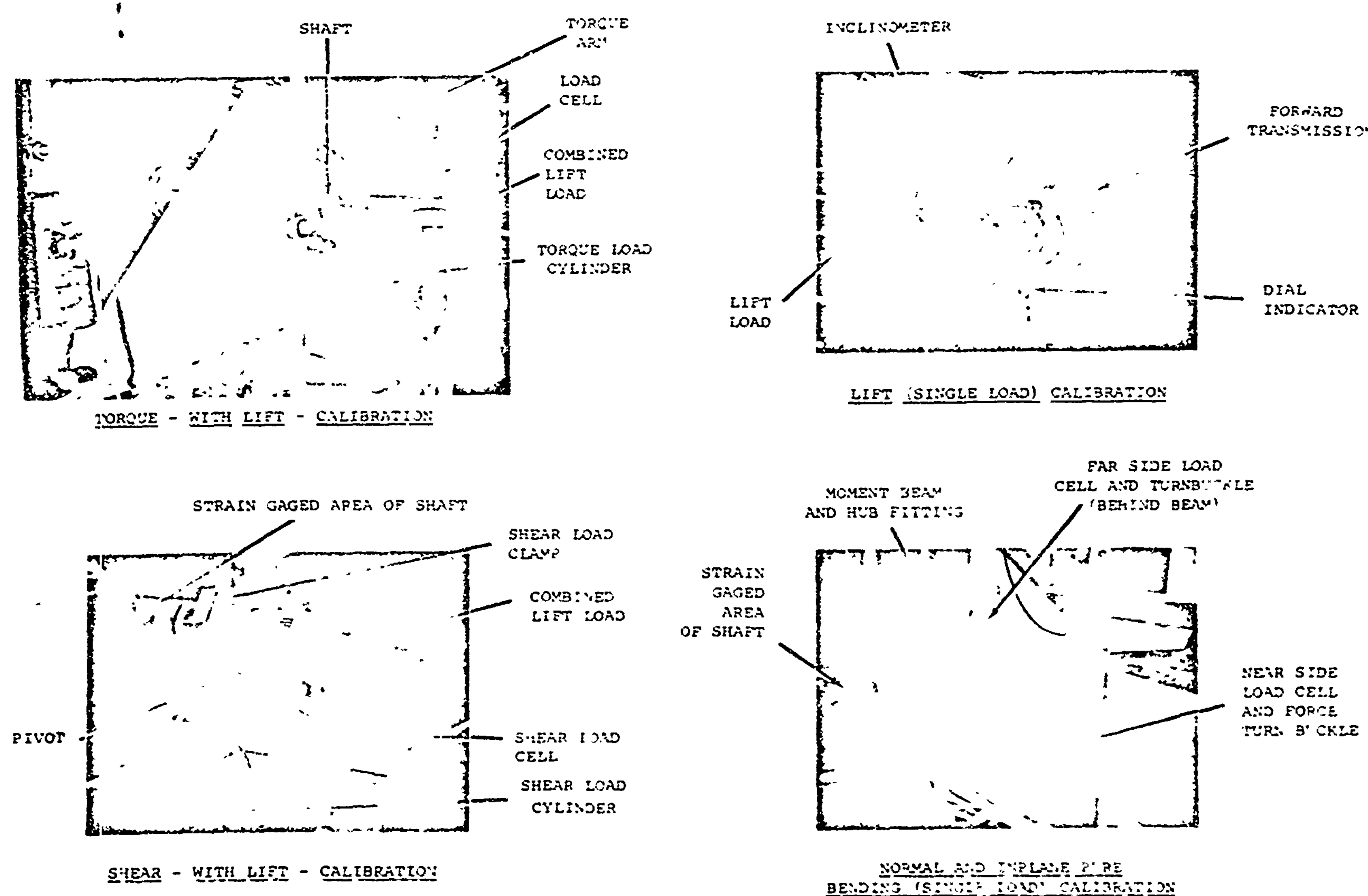
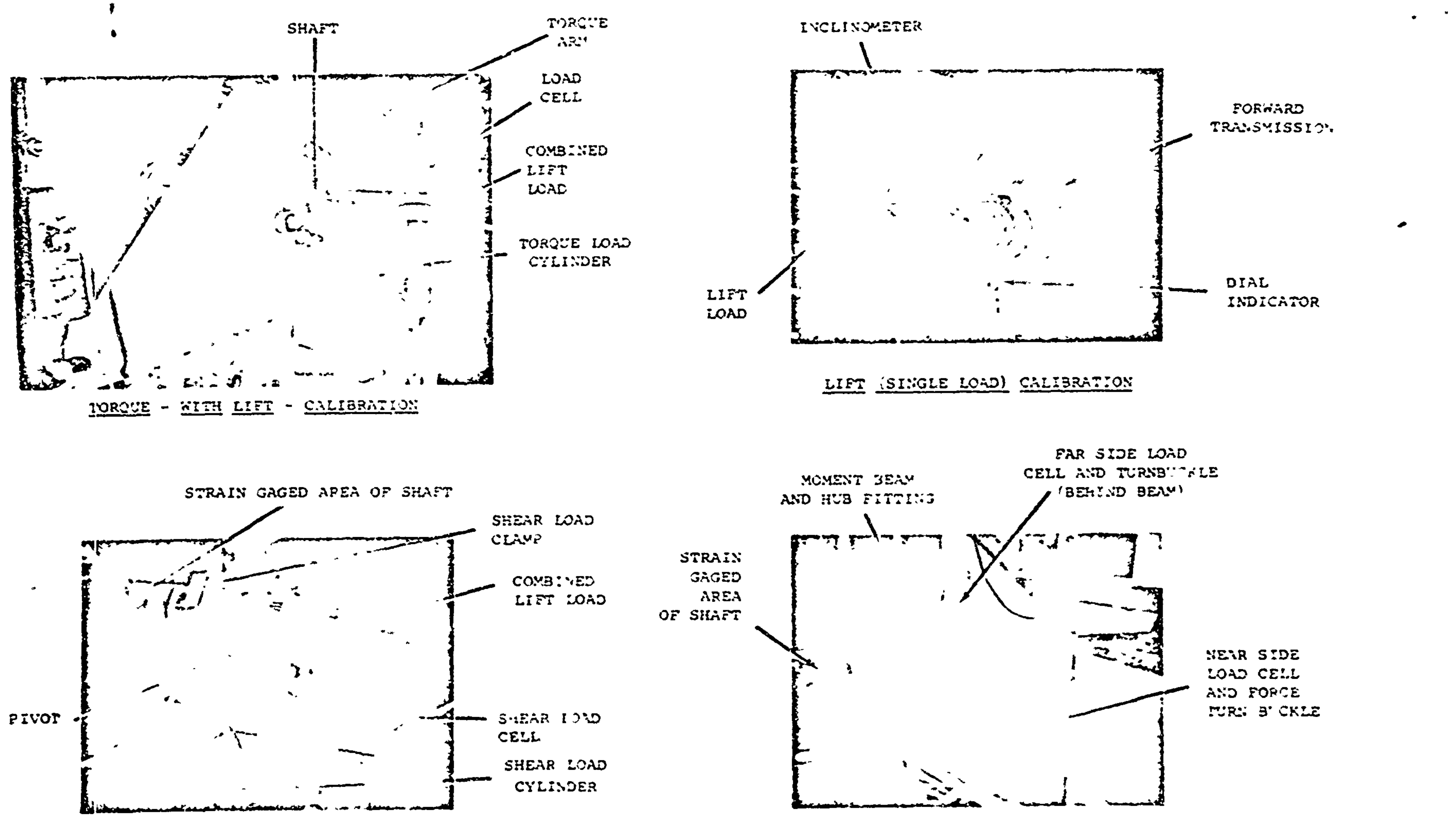


FIGURE 11. CALIBRATION OF LIFT, SHEAR AND MOMENT GAGES ON FORWARD ROTOR SHAFT



TORQUE - WITH LIFT - CALIBRATION

LIFT (SINGLE LOAD) CALIBRATION

SHEAR - WITH LIFT - CALIBRATION

NORMAL AND INPLANE PURE BENDING (SINGLE LOAD) CALIBRATION

FIGURE 11. CALIBRATION OF LIFT, SHEAR AND MOMENT GAGES ON FORWARD ROTOR SHAFT

calibrations can be deduced from Figure 12 which illustrates a summary of the hysteresis and deviations of the primary coefficient calibrations. In the majority of cases, it is shown that the calibrations had less than one percent uncertainty. It is believed that most of the larger values of hysteresis and deviation can be explained. For example, both rotor blades exhibit large errors in the calibration of the two chordwise gages which is believed to be due to hysteresis of the adhesive and fiberglass structure. Also, when first testing the rotor blades under combined loads joint friction was troublesome. Since the forward blade (which was calibrated second) shows much less error than the aft blade, it is believed that joint friction during calibration caused the larger error values shown for the aft blade. With these few exceptions, it is believed that a high degree of calibration accuracy was achieved and in every case the calibrations were deemed satisfactory.

The interaction calibration data were of a similar quality as may be noted from the data on the forward rotor shaft which are presented as an example in Figure 13. Generally, the interaction matrix which was obtained as a best fit of all calibration data shows all non-diagonal values to be small as compared to unity. Exceptions to this are the values in column 5 which apply to the gage which is designed to read shear about the 90-270 degree axis. This gage was apparently positioned with poor accuracy since the interactions with bending and tension are rather large. However, as shown in the table of the second part of the Figure 13, an evaluation of the maximum residual errors shows that the interaction coefficients utilized almost completely correct the 90 degree shear gage error. This maximum error table shows an excellent general accuracy with the largest errors of 4 and 5 percent being shown for the steady tension gage. Similar results were also obtained for the other rotor shaft and for the rotor blades.

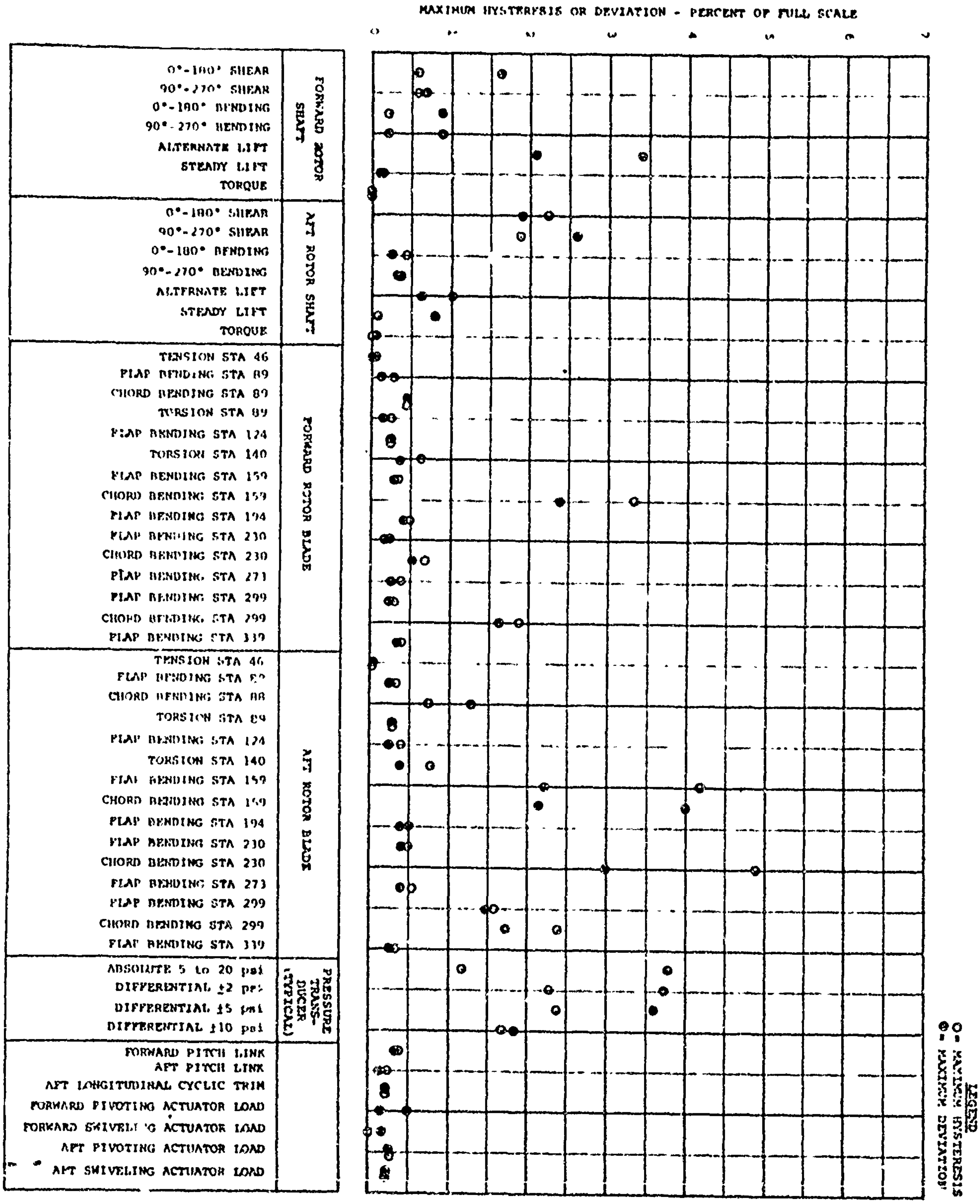


FIGURE 12. SUMMARY OF DATA ON THE QUALITY OF THE CALIBRATIONS

a. Interaction Matrix with Coefficient Definitions

$$\begin{bmatrix} \text{Interaction} \\ \text{Matrix} \\ \text{(Best Fit of} \\ \text{All Data)} \\ \\ \\ \end{bmatrix} = \begin{bmatrix} 1.00 & .00784 & .00556 & .155 & -.891 & .0245 \\ .0678 & 1.00 & -.0177 & .0400 & .654 & .0118 \\ -.0121 & -.0263 & 1.00 & .0487 & .166 & -.0755 \\ .0018 & -.0249 & .00441 & 1.00 & .134 & -.00140 \\ .0373 & .00333 & .00198 & -.134 & 1.00 & -.00416 \\ .0124 & -.00846 & .0260 & .201 & .359 & 1.00 \end{bmatrix}$$

Where

$$\underbrace{\begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \\ L_5 \\ L_6 \end{bmatrix}}_{\text{Actual Loads}} = \underbrace{\begin{bmatrix} 1.0 & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & 1.0 & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & 1.0 & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & 1.0 & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & 1.0 & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & 1.0 \end{bmatrix}}_{\text{Interaction Matrix}} \underbrace{\begin{bmatrix} R_1 & C_{11} \\ R_2 & C_{22} \\ R_3 & C_{33} \\ R_4 & C_{44} \\ R_5 & C_{55} \\ R_6 & C_{66} \end{bmatrix}}_{\text{Gage Readings} \quad \text{Primary Coefficients}}$$

And

L_1 and R_1 = Load and gage reading of bending moment about 90°-270° axis (respectively)
L_2 and R_2 = Load and gage reading of bending moment about 0-180° axis
L_3 and R_3 = Load and gage reading of torque
L_4 and R_4 = Load and gage reading of shear (0-180°)
L_5 and R_5 = Load and gage reading of shear (90-270°)
L_6 and R_6 = Load and gage reading of tension

b. Tabular Summary of Maximum Residual Errors

Loading Conditions	Type of Load	Bending 0°	Bending 90°	Torque	Shear 0°	Shear 90°	Steady Tension
Tension	Predicted Load:	868	774	-221	57.5	31.0	11,520
	Actual Load:	0	0	0	0	0	12,000
	Percent Error:	*1.1	*1.0	*0.03	*1.2	*0.6	4.0
Shear + Tension + Bend. Mom.	Predicted Load:	47,520	47,110	698	+3,522	-3,488	11,793
	Actual Load:	47,973	47,840	0	+3,531	-3,540	12,000
	Percent Error:	0.9	1.5	0.09	0.25	1.5	1.7
Torque + Tension	Predicted Load:	380	395.3	782,600	1.5	16.6	12,600
	Actual Load:	0	0	780,000	0	0	12,000
	Percent Error:	*0.4	*0.5	*0.3	*0.0	*0.0	5.0
Bend. Mom.	Predicted Load:	-76,000	76,700	648.2	21.7	73.8	130
	Actual Load:	-75,908	76,120	0	0	0	0
	Percent Error:	0.1	0.8	*0.08	*0.4	*1.0	*1.1

*The above errors are fractional errors unless the actual applied load is zero in which case the errors shown are fractions of the maximum load of that type which is applied.

FIGURE 13. INTERACTION MATRIX AND CALIBRATION EVALUATION FOR FORWARD ROTOR SHAFT

DATA REDUCTION AND ANALYSIS

PHILOSOPHY

The development of the Data System was to some degree influenced by our prior experience with semi-automatic systems. However, the cost of these manual reading-automatic recording systems greatly limited the amount of digitized data prepared. As a result, the flexibility and general usefulness of these test programs was very limited. It was decided, therefore, to consider all programs written for the semi-automatic system as obsolete. This past experience demonstrated the requirement for completely identified and standardized inputs and the usefulness of numerous specialized computer programs as compared to one large general program.

In implementing the new Data System, it was decided to provide the basic data calibration system with numerous options. The calibrated, harmonically analyzed and corrected data were then to be the input into an array of analytical programs. Finally a correlation program was provided to compare the output of the various analytical programs. This system required emphasis on meeting minimum pre-test requirements with provision for continuing long term development.

From a data acquisition viewpoint the features of the Data System which have been of particular usefulness are the so-called Quick Look option and the Data Check Program. With Quick Look the mandatory data and some particularly interesting data can be checked and processed in time so errors or malfunctions can be detected and corrected prior to the next test. The Data Check Program was used for automatic checking of voluminous data. This emphasis on prompt and complete data checking and evaluation has been the guiding philosophy of the project.

DATA SYSTEM CHARACTERISTICS

The flow of data through the data system is illustrated in Figure 14. Data begin to be combined and processed as soon as the flight test tape enters the Ground Station. First, certain signals from the tape are reproduced on an oscillogram so that record identification times can be identified. These intervals of data called edit times, together with the manual flight recordings, flight and run identifications, and instrumentation organization and identification data are input to the digitizing equipment together with the flight test tape. This equipment provides a fully identified data tape which consists of samples of up to 36 signals which have been obtained at a prescribed sampling rate. A total of seven passes through the equipment are required to obtain all of the data. As yet the data are not in engineering units. The digitized tapes are then taken to the Central Computing Center where they are input into an IBM 7044 computer together with the calibration data and various calibration and analysis programs.

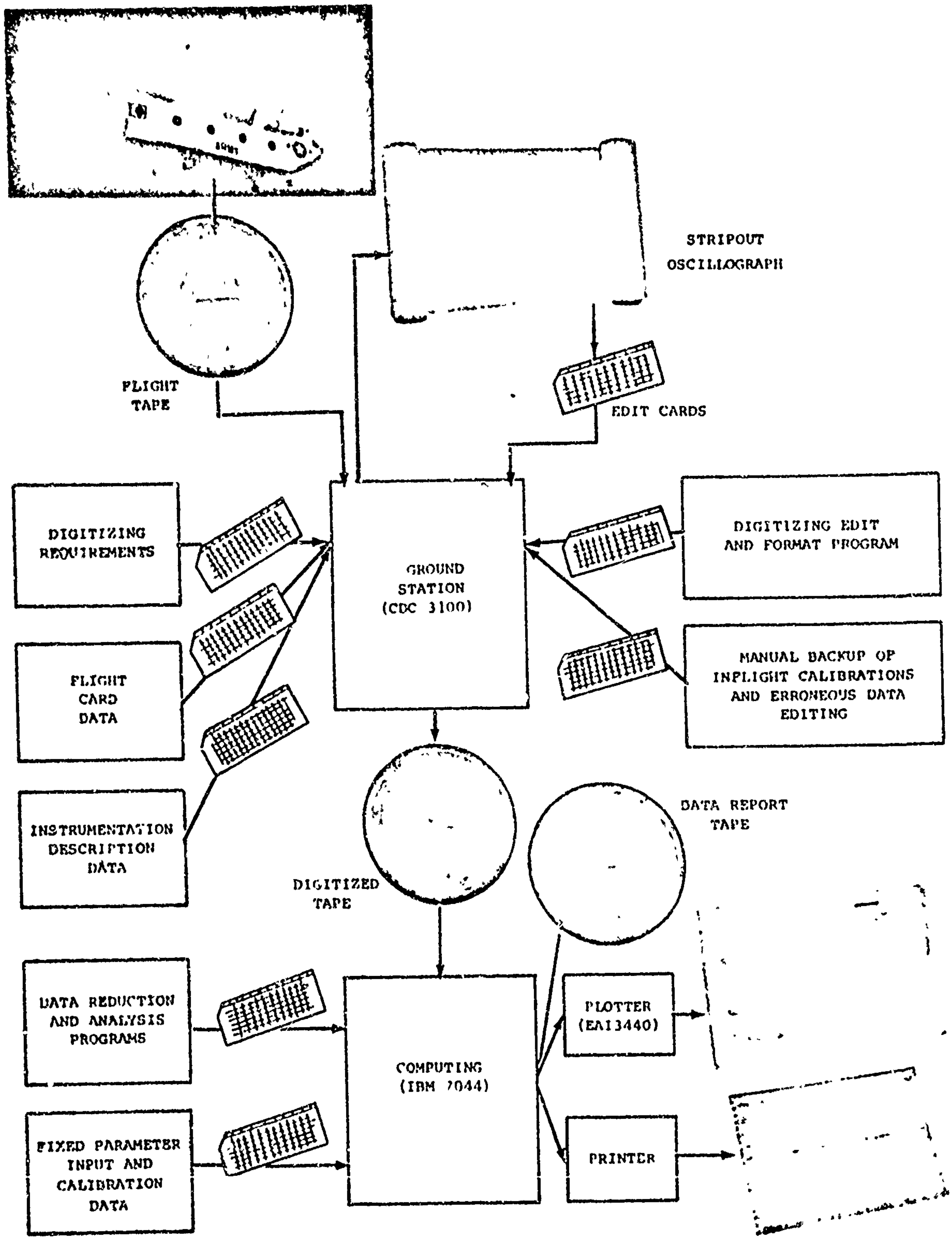


FIGURE 14. DATA FLOW SCHEMATIC

Output from these programs is in the form of listings and automatic plots.

The calibration and analysis programs are arranged as shown in the Figure 15 block diagram. All programs encountered up to and including the Interaction Corrections program are collectively referred to as the Calibration programs even though some analysis and considerable checking is also performed. Following the Inter-action corrections program, the data are input sequentially into the various analytical programs. Selected output from these several programs are then input together with detailed analytical and other inputs in the Comparisons program.

As mentioned previously all of these programs had standardized input and output format so that specified programs could be deleted or added as desired.

The standardized magnetic tape data record consisted of a standard forty-two word header of flight, run, and parameter information followed by a varying number of data words. Every record had identical tape format and carried its own identification as to the type of data and the generating program. Thus, each piece of information was complete in itself and could be used in any suitable program. In fact, this approach provided such flexibility that further identification had to be added to indicate which calibration processes had been applied to the data.

In the sequence of calibration programs, the first program encountered performs most of the routine calibration tasks. This program called the Static Calibration (linear and standard nonlinear) program executes the following tasks:

1. Calculates real engineering values from digitized counts, using card input equivalents and an automatic six step pre-flight calibration.
2. Corrects all data for circuit drift by use of inflight calibrations.
3. Calculates true airspeed and density altitude from both card and digitized data input. If any digitized input is missing, program automatically takes required values from card input. When calculating true airspeed, up to five different position error curves based on the maneuver being considered may be used.
4. Corrects up to ten parameters for non-linearity.
5. Corrects errors or omissions in card input.
6. Checks for faulty card input and takes appropriate action if encountered.
7. Automatically handles up to three passes of data.
8. When desired, will identify rotor azimuth and block data into records of one rotor revolution each.
9. Calculates interval time between samples.
10. Sorts all data into run or data code order as desired.

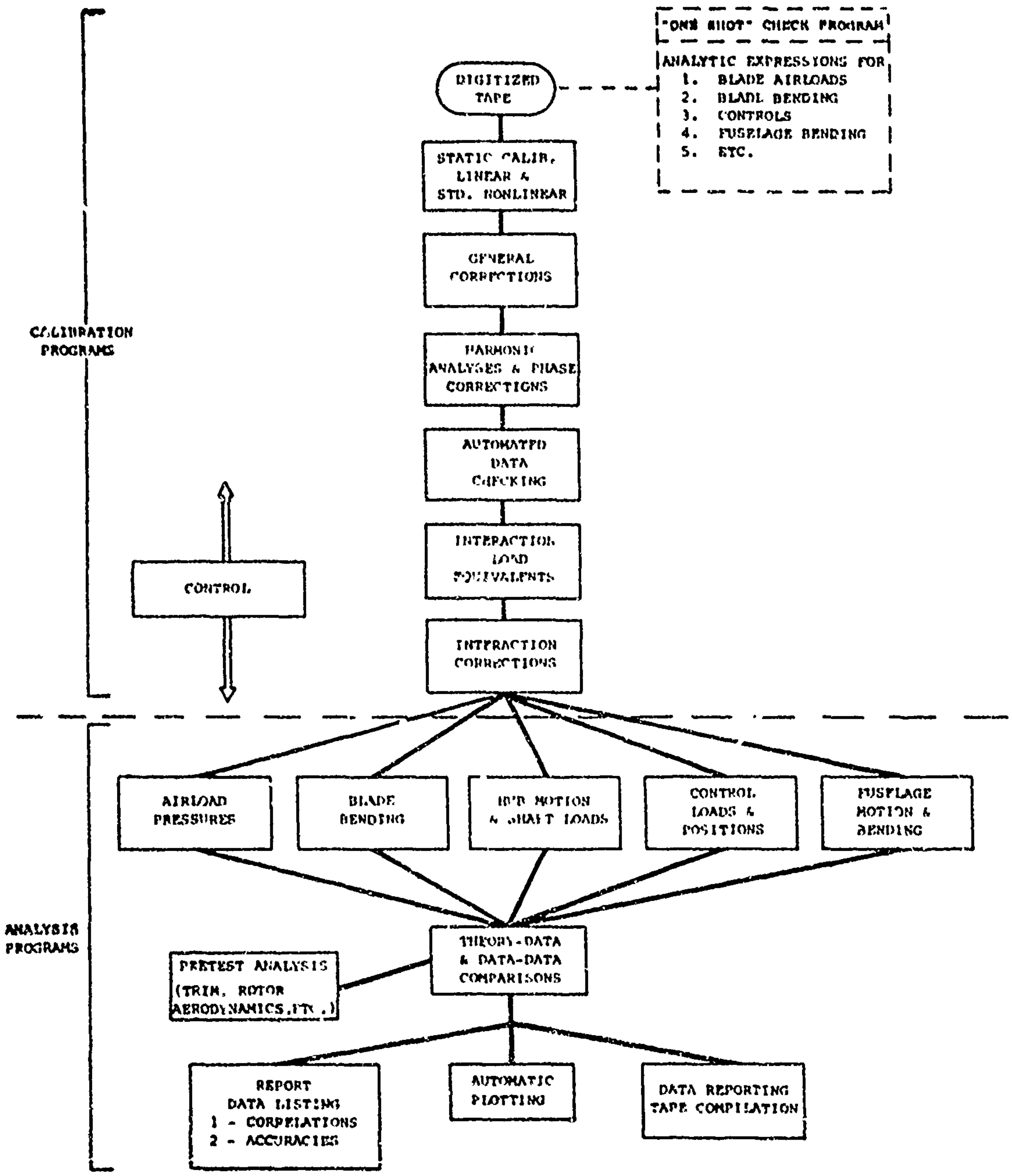


FIGURE 15. BLOCK DIAGRAM OF DATA CALIBRATION ANALYSIS AND EVALUATION SYSTEM

This program provides an output data tape in standard format and an input-output listing for error analysis.

The next program encountered by the data is called the General Corrections Program. This program continues the non-linearity and temperature corrections which were started in the Calibration Program, but could not be completed due to computer memory limitations. The major effort is required to correct for the small non-linearity of the differential pressure transducers and to correct all of the pressure transducers for temperature effects.

Up to this point all data are considered as individual samples of static data. However, with rotorcraft data the emphasis is on the dynamic portion of the signals. In fact, some signals are produced with the steady load component suppressed completely. The processing of such data requires harmonic analysis as a routine part of the system. A secondary problem is the consideration of subharmonic oscillations. Due to aircraft motions and other low frequency phenomena, subsequent cycles of data can vary significantly. It was decided to record, digitize, calibrate and harmonically analyze five cycles of data and then to average and measure the variations between cycles prior to further analysis. In this manner, the harmonic coefficients were determined and the repeatability of these coefficients among adjacent rotor cycles was evaluated. The Harmonic Analysis and Phase Correction program accepts an output tape from either the Calibration or the General Correction program together with input decks of phase corrections and frequency sensitivity parameters and performs the following tasks:

1. Compute a standard N-point harmonic analysis on 10 to 100 ordinates, calculating the steady term, and any desired number of harmonic components up to (N-1)/2.
2. Correct harmonic components for incorrect rotor azimuth, phase lag of the recording system, and phase lag of the rotor azimuth signal.
3. Correct any parameter for frequency sensitivity.
4. Check for erroneous input.
5. Calculate acceleration, when desired, from displacement.
6. Calculate certain basic analysis values and coefficients for use in later programs; notably, run gross weight, run center of gravity of test point, advance ratio, and thrust coefficient.
7. Average, when desired, up to 99 successive cycles per run.

This program produces the usual data tape in standard format and an error listing identifying incorrect input, if encountered.

Continuing, the next data programs encountered are the Interaction Load Equivalents and the Interaction Correction Programs. It is the purpose of the Interaction Correction Program to perform the matrix multiplications required to correct the data for the interactions discussed previously. This operation

is performed on the harmonic coefficients. This is valid since the calibrations involved were found to be linear. If these functions were non-linear, the interaction corrections would have to be performed to each of the data samples at a much greater expenditure of computer time . The Interaction Load Equivalents Program is required because many stations on the rotor blades and some combinations of the spare gages on the rotor shafts produce insufficient load values to complete the interaction correction operations. Rather than neglect these corrections, it was deemed more accurate to provide extrapolation routines to determine the required values from the adjacent measurements. Since the interactions in question were relatively small, the so-called Interaction Load Equivalents were calculated from the measurements before the interaction corrections were applied.

As shown in Figure 15, the Automated Data Checking program is not directly a part of the data path since the data are not changed as a result of this program, however, all test data are processed by this program. This program is considered to be a paramount feature, if not an essential part of the Data System. Error identification was given this attention due to the decreased visibility of digitized data and the large increase in the volume of data reduced. The usual hand checking of plots and listings which is never very efficient could not cope with the automatic digitizing system. To relieve this condition, all programs were given a series of internal error checks to identify missing input, unreasonable computations, programs run in illogical order, etc. In addition, the General Check Program was written to specifically test all reduced values against predicted values. The analysis method was based on the fact that most helicopter test data varies predictably with airspeed. This allows an envelope to be generated for each parameter which all data should lie within. The computer program, using simple interpolation sends an error message denoting any values that fall outside the envelope. A typical check envelope is shown in Figure 16.

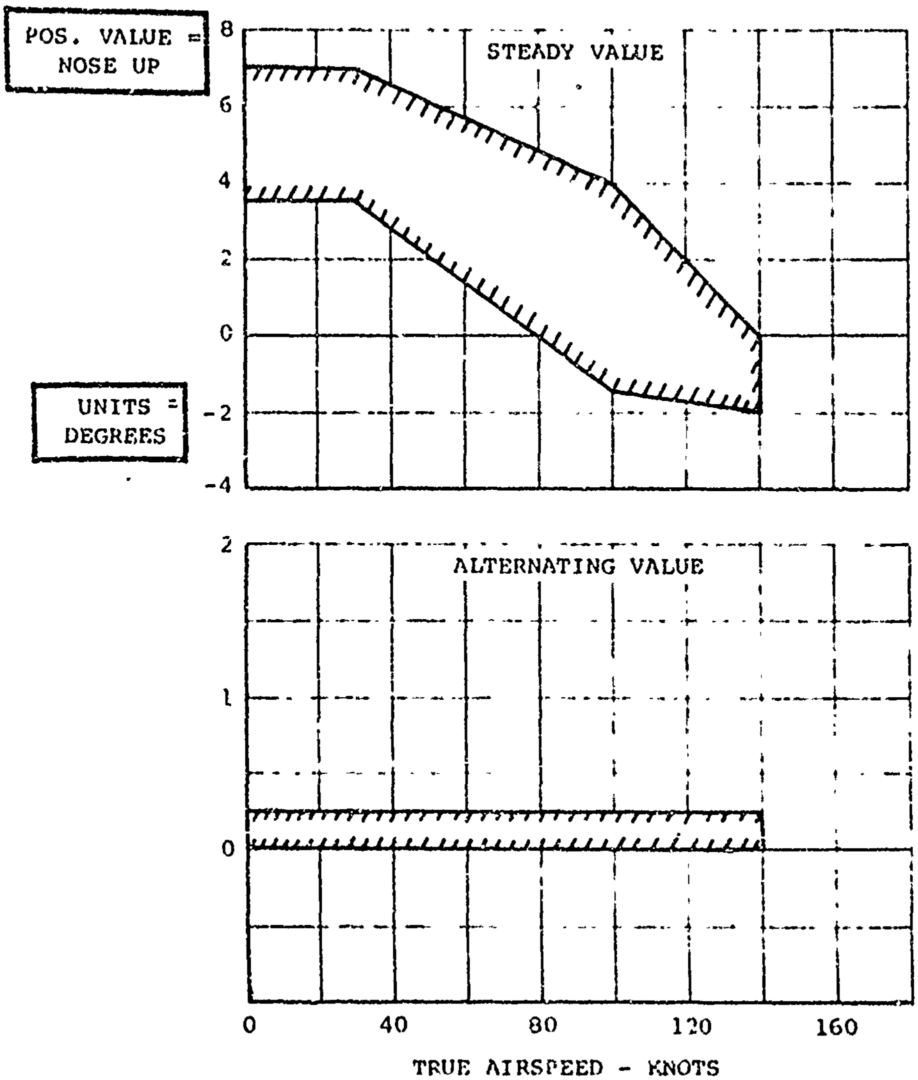
To further improve the data checking, corrections were provided for those helicopter parameters which vary predictably with the ratio of thrust coefficient to rotor solidity ratio and rotor advance ratio. Therefore, when desired, the program will use these terms to standardize the values of any desired parameter to a baseline value before interpolation. This baseline may be any set of gross weight, center of gravity, altitude, and rotor rpm conditions for which there exists enough data to construct an envelope. Note that this program serves the double purpose of not only detecting error, but also giving immediate warning of unexpected data values in a program, as data outside an envelope are not necessarily an error.

PARAMETER: PITCH ATTITUDE CODE: 3052

STATION/SPAN: 235 WATERLINE CHORD: -13.0 BUTT: 0

OPTION: 12 LOCATION: CABIN ENDURANCE LIMIT: NONE

MANEUVER FACTOR: NONE TRANSITION FACTOR: NONE



SOURCE: TEST CONDITIONS AND PROGRAM A-81

FIGURE 16. TYPICAL ENVELOPE USED IN AUTOMATED DATA CHECKING

Once the data are calibrated and checked, a small part of the data are output in listings or plots and are not processed further. By far the majority of the data are of little value in this form and must be combined with other data before the results assume stature. For example, the Airload Pressures program processed the separate pressure measurements into the following values:

1. At each blade station with a chordwise pressure survey, lift and pitching moment per unit span were obtained.
2. Integrations over the blade were performed to obtain the blade flapping moment and blade root pitching moment.

These data were of considerable value in themselves and were also used as input to the Comparison Program for further analysis.

The next program prepared to analyze the data was the Blade Bending program which processed and related the blade strain gage readings. Blade bending data were resolved into blade deflection mode shapes at various amplitudes and phase relations. This analysis also computed the apparent lift forces which were required to cause the measured bending for comparison with the measured lift data.

The Hub Motion and Shaft Loads program processed the rotating shaft strain gage data and the rotating hub accelerometers and converted the data to forces, moments and motions with respect to fixed axes. Similarly, the control and fuselage data were processed through programs devised to relate and obtain the maximum value from the measurements obtained. All data were prepared for automatic plotting and a standardized output tape was prepared by each program for further analysis.

The purpose of the Correlation program was to provide comparisons between various measured data and between input data from other tests and input theoretical values. This program provides for data comparisons which relate various measurements on the basis of component equilibrium (redundancy) to ensure consistency and to determine accuracy. All outputs were prepared for automatic plotting in prescribed formats. Output listings of all data considered were provided with documentation of the data source. A significant new contribution of this program was the start of the analysis of airloads data into time-dependent aerodynamic coefficients. This analysis required input of theoretical values of blade section angle of attack and other aerodynamic parameters. These theoretical values were obtained from the program described in Reference 1. Test data from other airloads measurement programs are also available and these data are being processed and prepared for comparison.

CHECKOUT AND SUBSTANTIATION OF SYSTEM

The procedures necessary to ensure that a Data System of this magnitude is working properly require more thought and effort than is required to devise and create the system. The equipment must be checked against known signals, programs must be checked (individually and together) and the instrumentation must be functionally checked through the System to ensure that all steps are working properly. Each component of the System must be fail-safe in operation so that incompatible data (either magnitude of values or quantity of measurements) caused by unexpected results or equipment failures do not allow undetected processing of erroneous measurements. The general philosophy followed was to check that when an unexpected value or operational situation occurred, the System would print an error message and not continue if further errors to the correct data would result.

The checkout of the equipment mainly consisted of operational tests with known electrical signals inserted on the input tapes and with various digitizing procedures and combinations of standardizing signals. Due to the many possible combinations involved these tests were more difficult and time consuming than expected. The digitizing unit control computer program required some modification as a result of these tests to provide consistent, substantiated, data output.

The calibration and analysis programs were checked using static values obtained from the equipment check tapes and routine card inputs. During checkout these programs were modified to print out each step of the operation from input to output. These numerous output statements were removed when the program was considered operational. Test cases were generated to check out each routine individually and then in total. For example, if a program had two equations, three test cases were used, one to check the first equation only, one to check the second equation only, and one to check both equations together. On any program using more than the simplest analysis, test cases were always generated from data similarly analyzed to detect and evaluate any differences in the new programmed routine. This is particularly important when using integration, matrix inversion, etc., where different routines for the same solution may give slightly different answers. A large magnitude test case was also run using the maximum allowed input to check storage and special tape routines for handling large amounts of data.

It was also possible to check the Data System against flight test data which was previously processed by the semi-automatic data reduction system. These flight data consisted of complicated wave forms which were digitized and compared with the semi-automatic data reduction of the peak-to-peak loads. Also, the wave forms were compared to the oscillograms. These checks gave

satisfactory results with a good reproduction of the wave form and numerical results comparing within the reading resolution of the semi-automatic system. Typical values obtained for one channel were:

	Maximum Peak	Minimum Peak
Semi-Automatic	210.5	73.8
A/D Converter	206.2	71.8
Difference	4.3	2.0

This check did not give a conclusive indication of data reduction accuracy since the correct signal values were not known. However, similar results were also obtained for a fairly large sample of similar data.

The most extensive check of the system computer programs with dynamic data was obtained with the program check program. This so-called One Shot Check program, noted on Figure 15, used analytic expressions for simulating flight data such that the final output results from all programs could be checked. A computer program was required for this purpose due to the large amount of data input required to simulate the high digitizing rate (10,000 point/second) of the equipment. For the One Shot check case, data for all channels during five rotor revolutions of each rotor were simulated with different input constants for each revolution. With approximately 200 oscillating data channels (and the remaining channels constant with time), the check case input approximately 62,500 values. Obviously manual computation of this quantity of data would have been prohibitively time consuming and costly. Since this program prepared a card input to the Ground Station computer, a thorough check of all programs was provided.

RESULTS PRESENTATIONS

In the preparation of results, the guiding principles were to obtain illustrations as to quality of the test as well as the test data and to make as complete and concise a presentation as possible. Since a program of this magnitude can raise many problems, these problems tend to become exaggerated. To overcome this tendency, the measurement of how well the test was being conducted proved worthwhile. The effort required to make every data presentation a complete unity has reduced confusion and is also reflected in the final data presentations. It should be noted that the magnitude of the results of this program is almost overwhelming with approximately 12 million data samples obtained. Tabular listings of this magnitude of data in report format, would form a data report four and one-half feet thick without including the analyzed data output. Plots for this program are expected to reach 20,000 pages before completion. There is obvious need for data digestion and conciseness of the presentations to reduce this volume to a presentable report form.

A difficulty encountered in results presentation from such a program is the creation of a machine printable language. Easily interpretable substitutes must be found for the Greek and other unprintable symbols to which engineers have become attached. For example, in this program the blade flapping angle which is commonly β is reduced to FLAP. The Fourier coefficients of β which are commonly, a_0, a1, b_1, etc., are reduced to FLAP (K, T); where K is an integer denoting the harmonic and T is an integer denoting the trigonometric function which is being considered. Thus:

$$\beta = a \quad + a_0 \text{ Sin } \psi \quad + b_1 \text{ Cos } \psi + \ldots$$

is reduced to

$$\text{FLAP} = \sum_{K-o}^{K=N} \sum_{T=1}^{T=2} \text{FLAP (K,T) [Appropriate Function]}$$

While in this form the simplification is not apparent, the symbol FLAP (K, T) is easily defined and is machine printable. Also, the integers T - 3 and T 4 can be used to denote the resultant coefficients and phase angle respectively so that further simplifications of data preparation and identification are possible. With the enormous output of this program such simplifications were believed mandatory.

It is unfortunate that, at the time of the preparation of this paper, insufficient experience had been acquired with the system for the company to publish results. Thorough substantiation of the plans and philosophies given previously, must therefore be postponed. The airloads data shown in Figure 17 are typical

of the results expected. As shown, the theory will predict the general shape and most of the complications of the airloadings. However, to improve the prediction of the higher harmonics of rotor vibratory loads, a better understanding of rotor aerodynamics is required.

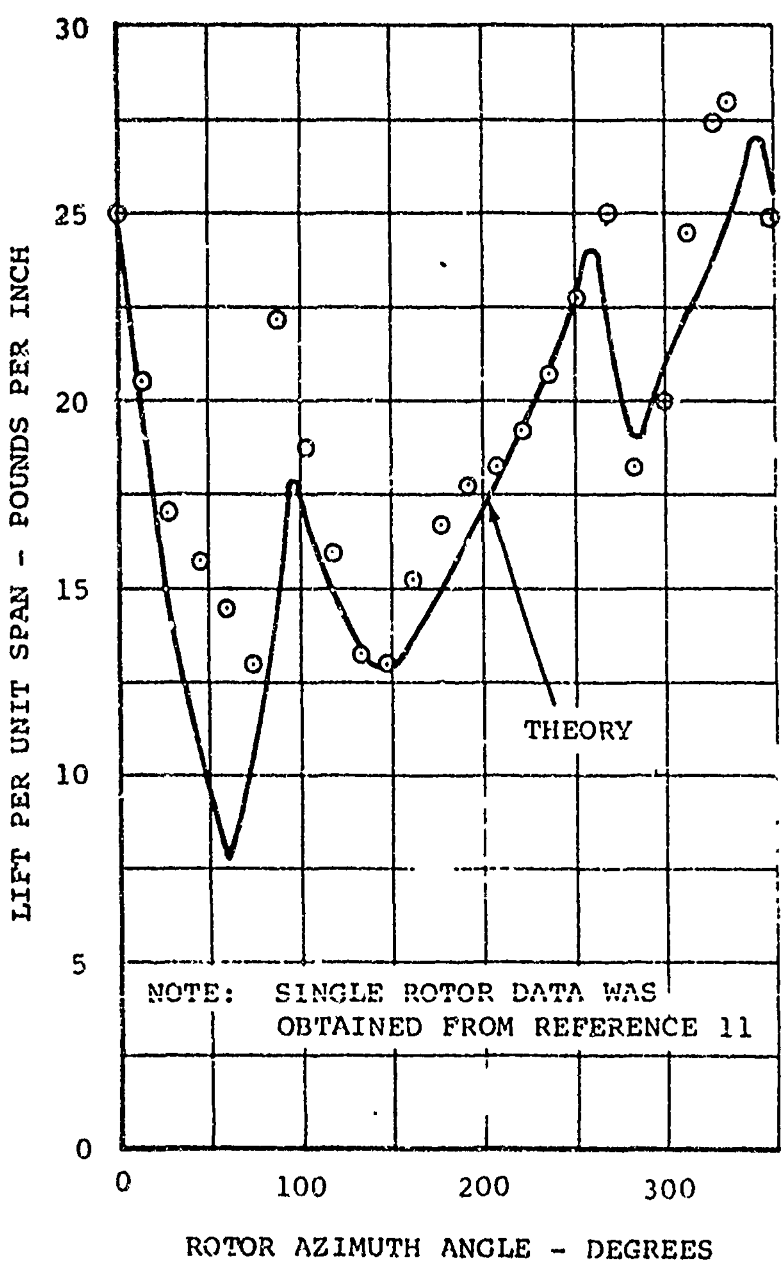


FIGURE 17. COMPARISON OF AZIMUTHAL VARIATION OF LIFT PER UNIT SPAN FOR SINGLE ROTOR DATA AND THEORY.

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